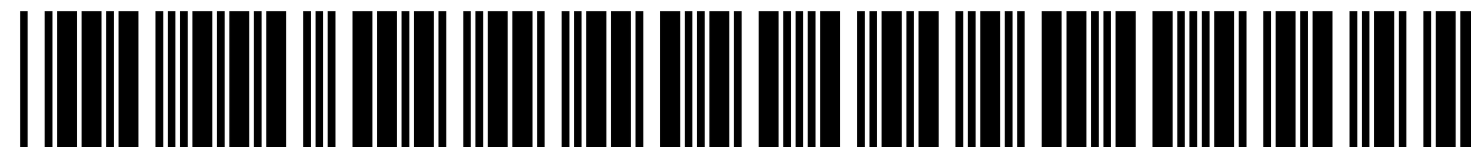


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**Yoneda et al.**

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(45) **Date of Patent: Jan. 10, 2023**

(54) **OPTICAL WAVEGUIDE TYPE PHOTODETECTOR**

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(51) **Int. Cl.**

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| ***H01L 31/0232*** | (2014.01) |
| ***H01L 31/109*** | (2006.01) |
| ***H01L 31/0304*** | (2006.01) |

(52) **U.S. Cl.**
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(58) **Field of Classification Search**
CPC ..... H01L 31/02327; H01L 31/145–153; H01L 31/03046; H01L 31/109
See application file for complete search history.

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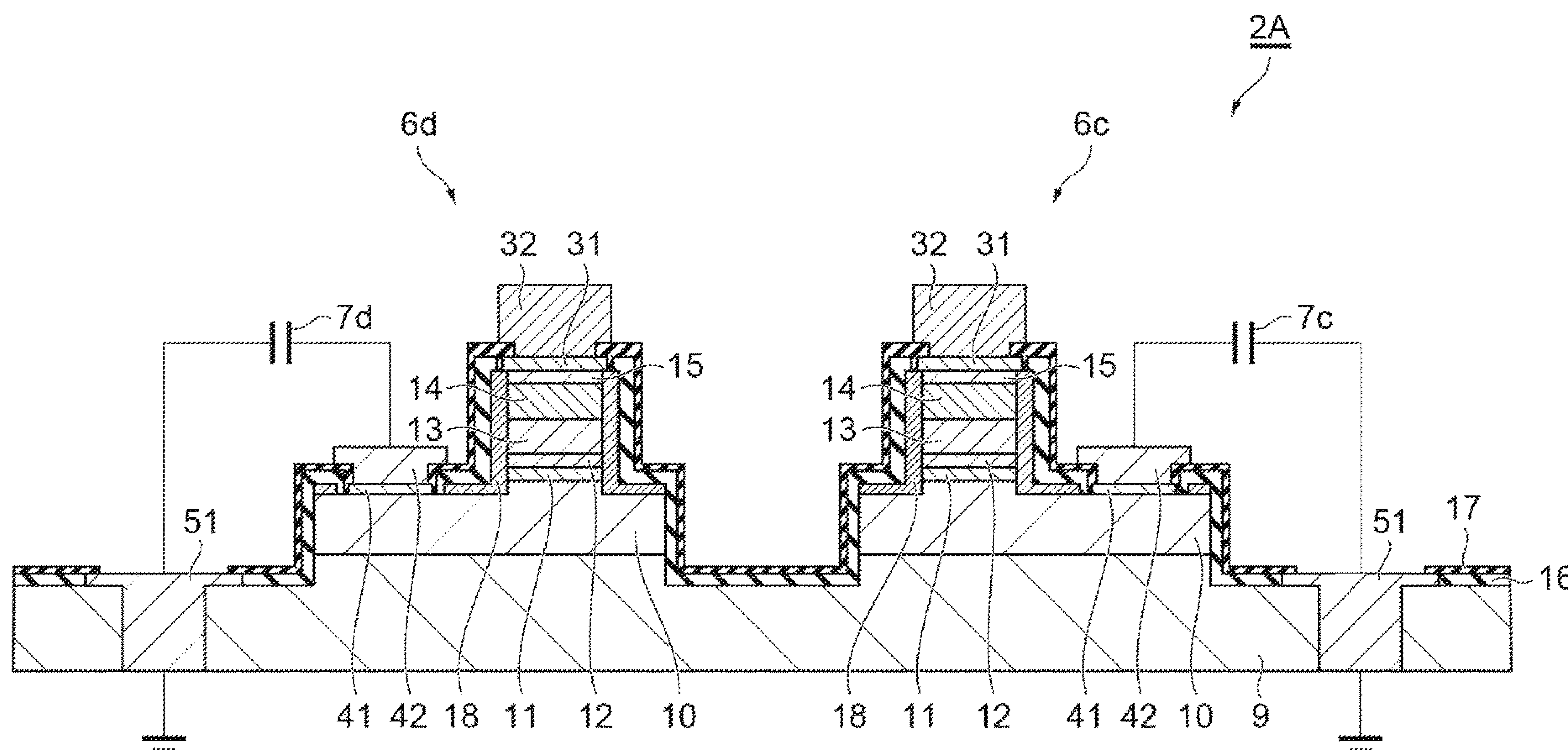
(57) **ABSTRACT**

An optical waveguide type photodetector includes a first semiconductor layer of a first conductive type, a multiplication layer of a first conductive type on the first semiconductor layer, an optical waveguide structure, and a photodiode structure. The photodiode structure has a third semiconductor layer of a second conductive type, an optical absorption layer of an intrinsic conductive type or of a second conductive type, and a second semiconductor layer of a second conductive type. The optical waveguide structure includes an optical waveguiding core layer and a cladding layer. An end face of the photodiode structure located in a second region of the first semiconductor layer and an end face of the optical waveguide structure located in a first region of the first semiconductor layer are in contact.

**16 Claims, 14 Drawing Sheets**



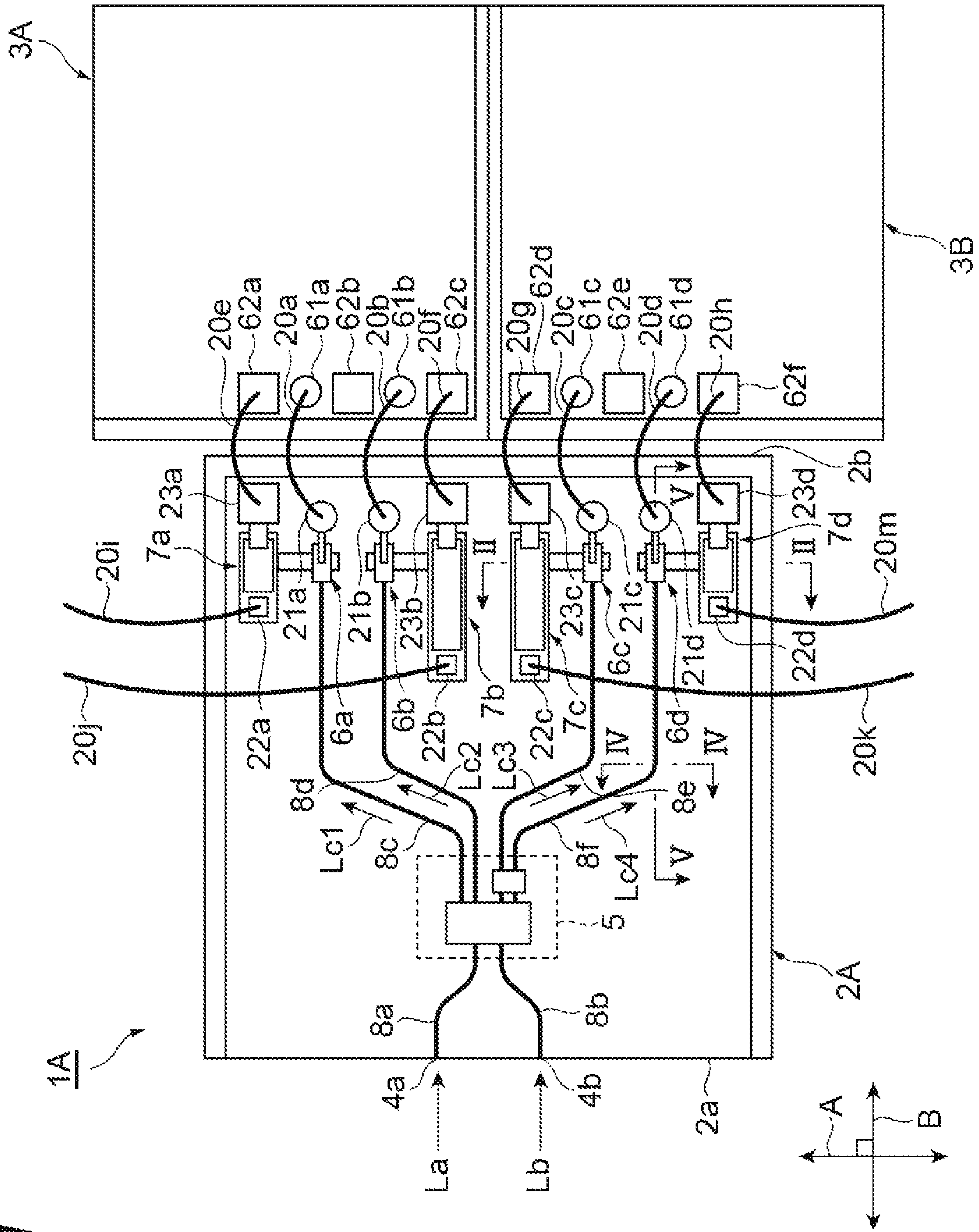



*Fig.1*

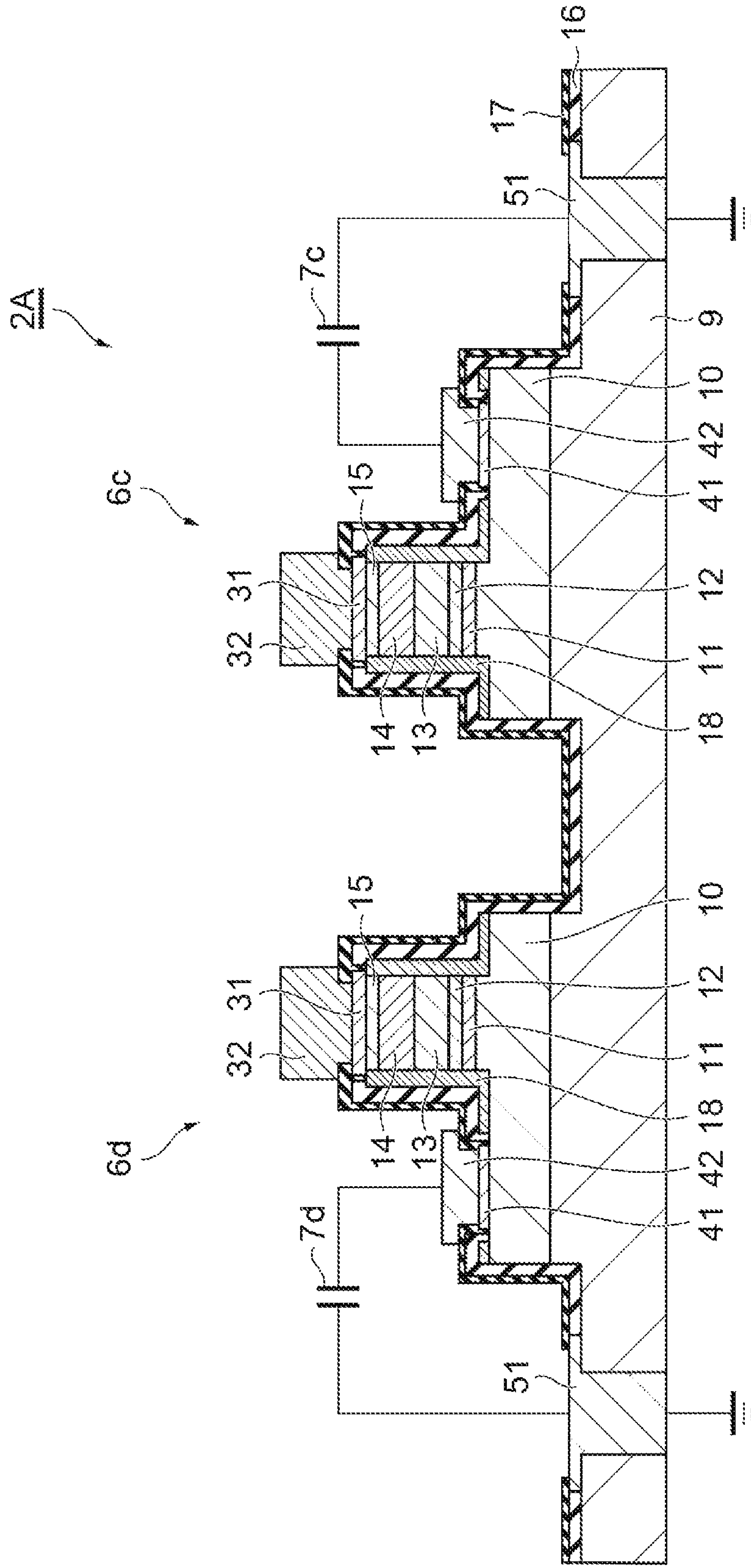
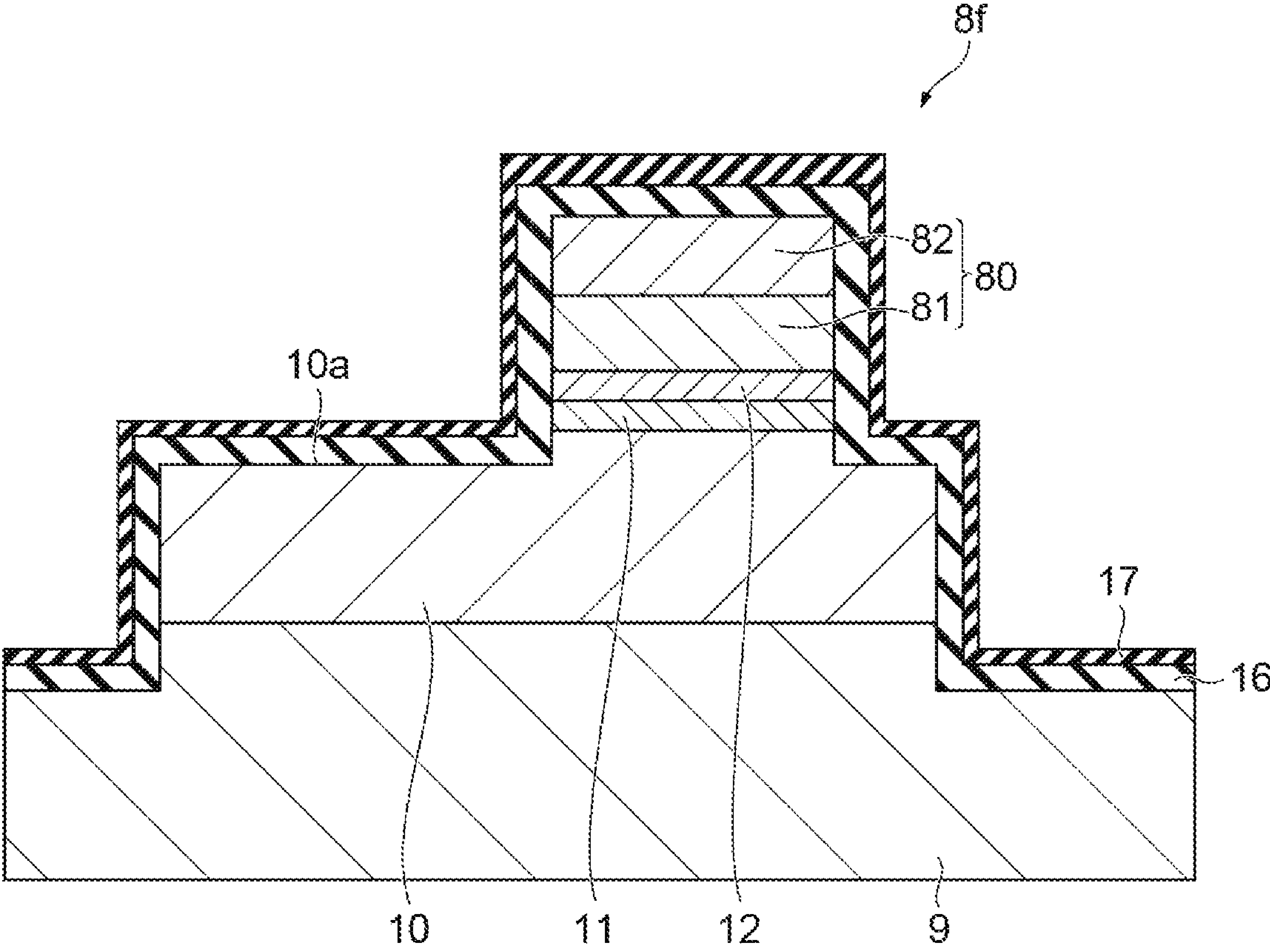


Fig.2
2A
6c
6d
7c
7d
9
10
11
12
13
14
15
16
17
18
31
32
41
42
51

*Fig.3*

6d
32
31
15
14
19
13
18
41
42
18
17
16
10
11
12
9
19

*Fig.4*



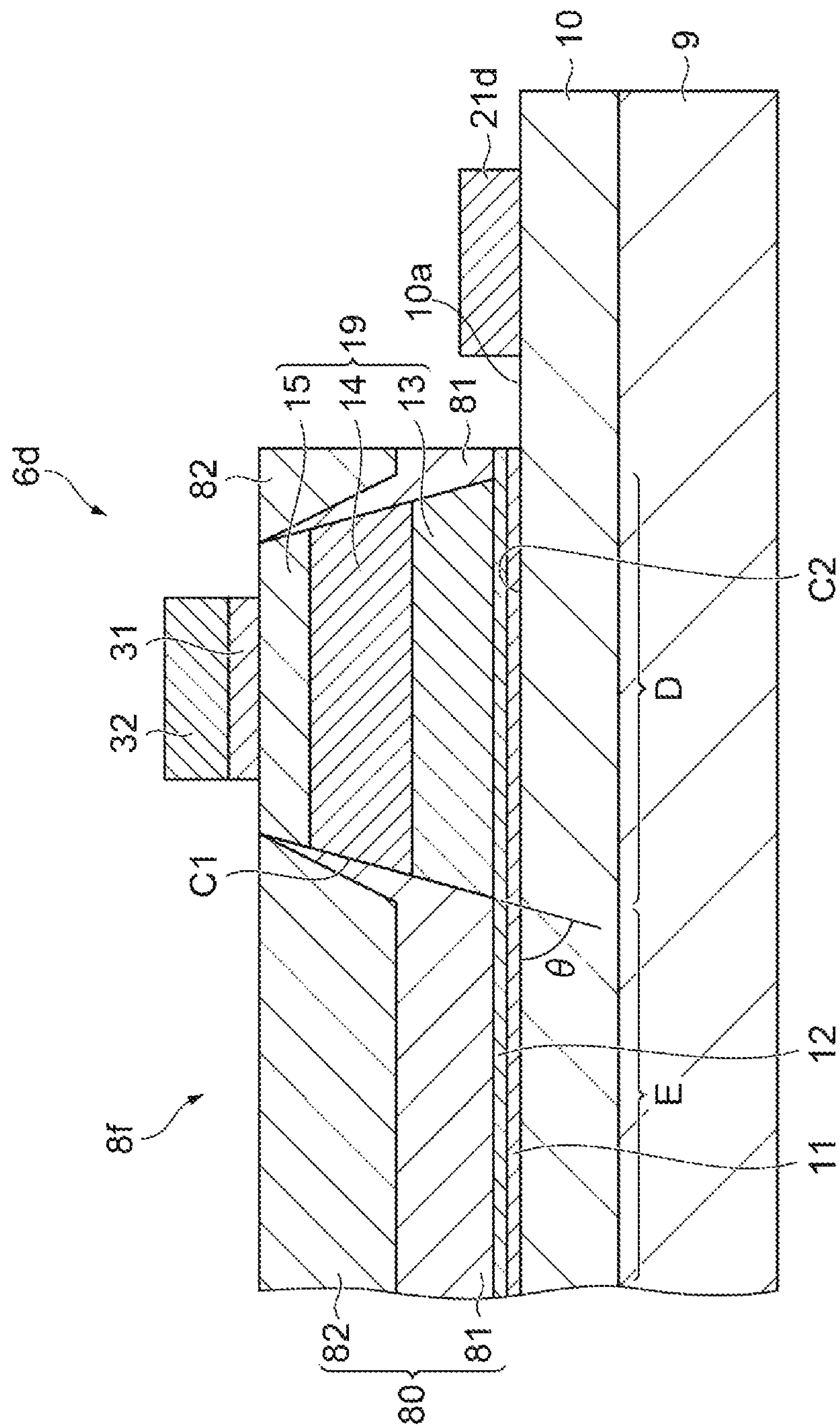



Fig.5

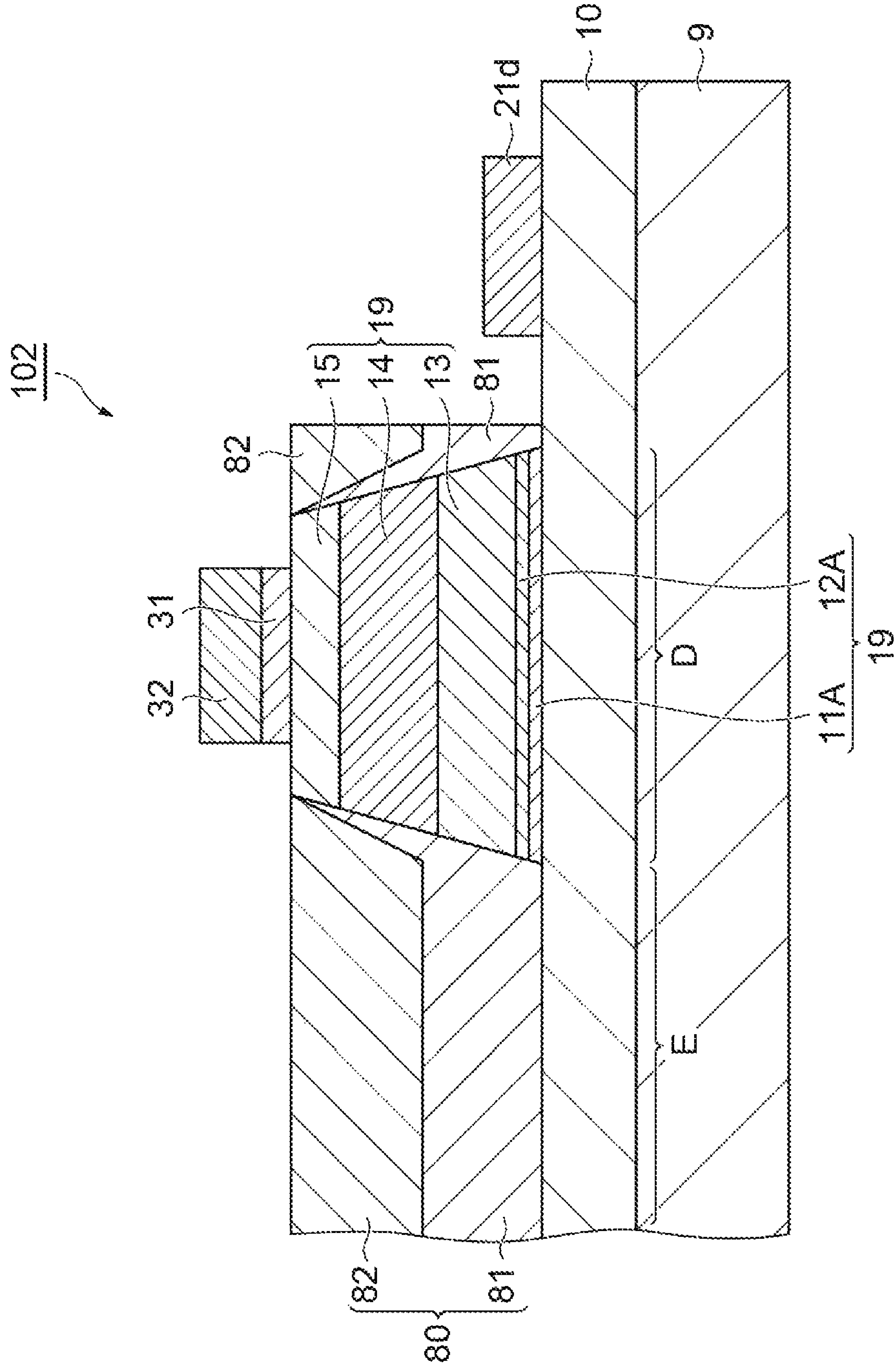



*Fig.6*

Fig.7A

81
11j
10
Ws
Wc
13
p+
i(n-)
n+
12A
11A

Fig.7B

ELECTRIC FIELD INTENSITY
Emax1
Emax2
G11
G12
POSITION IN THICKNESS DIRECTION

*Fig.8A*

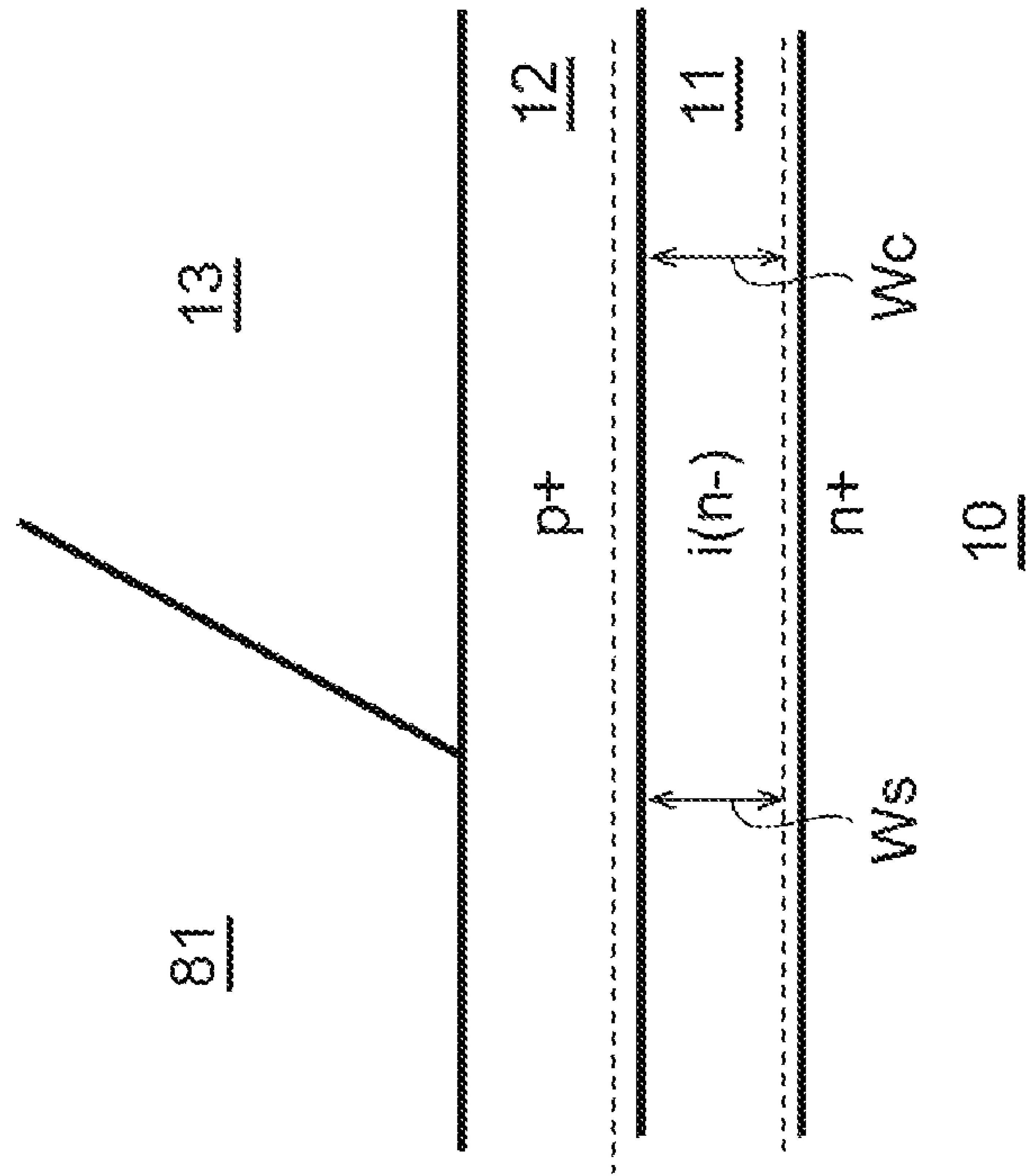
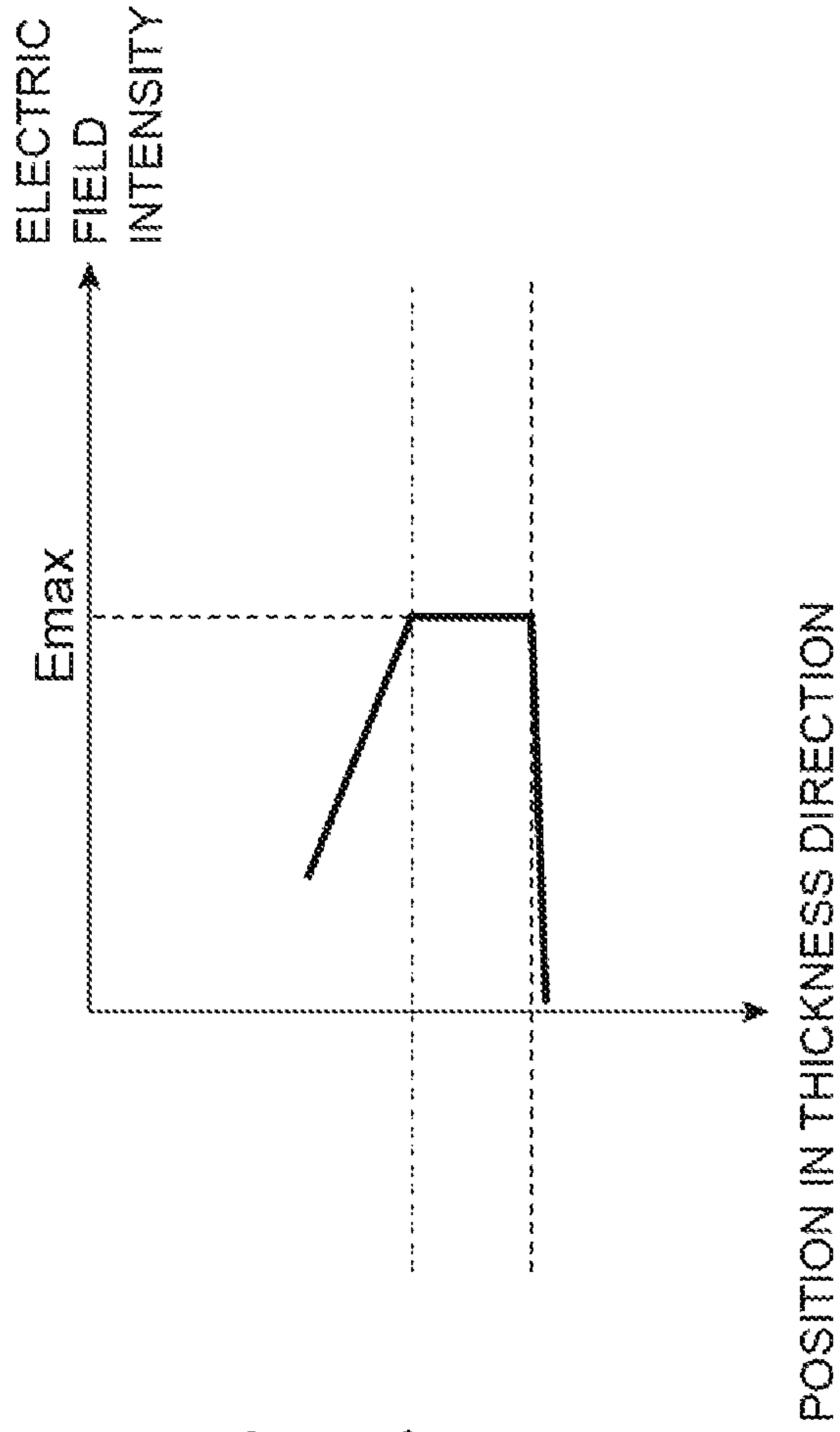



*Fig.8B*



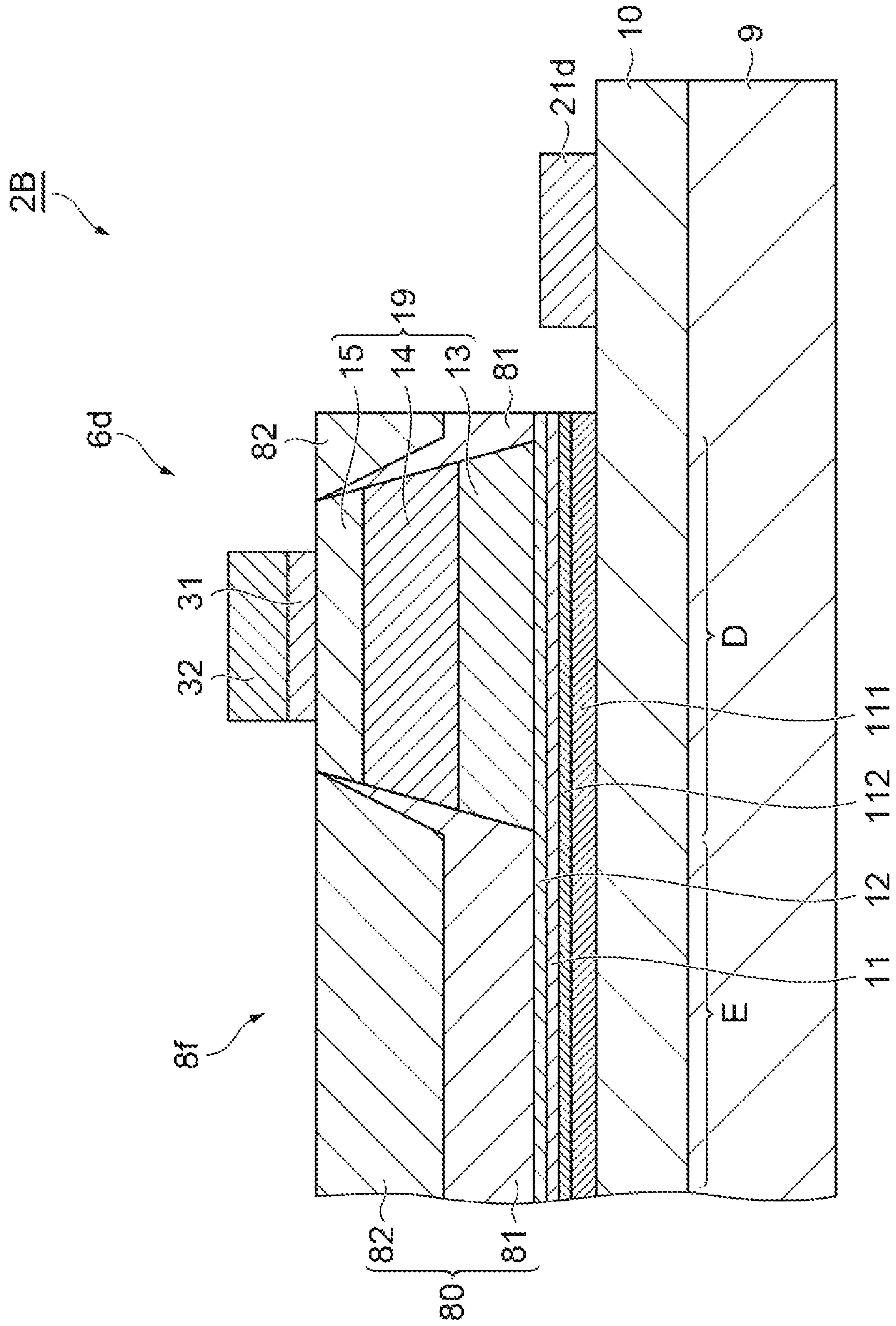


Fig.9
2B
6d
8f
19
15
14
13
81
82
31
32
21d
10
9
D
E
111
112
12
11
80

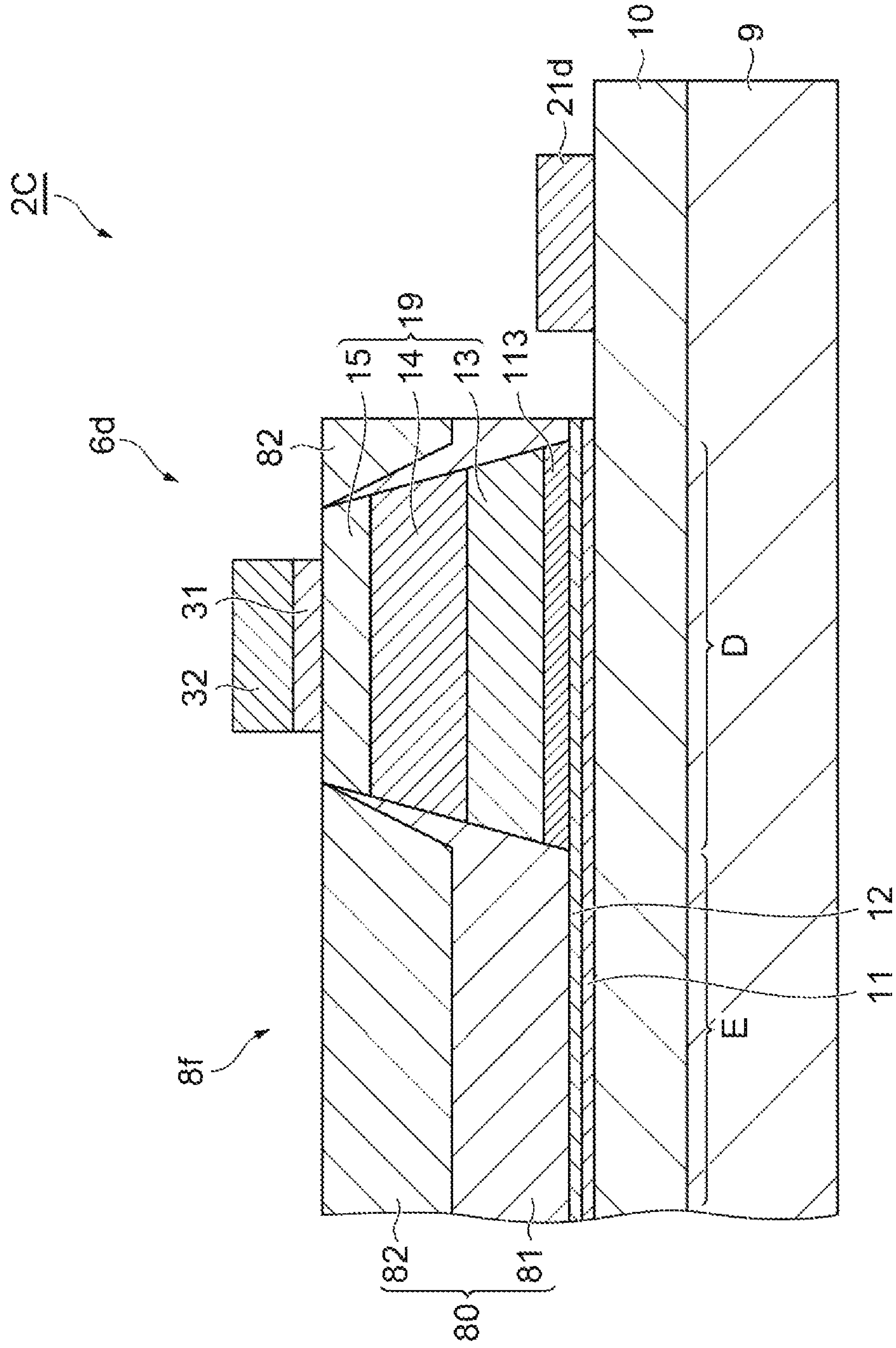



Fig.10

*Fig.11*

2D
6d
8f
21d
101
9
117
116
115
114
12C
11C
D
E
131
132
82
81
80

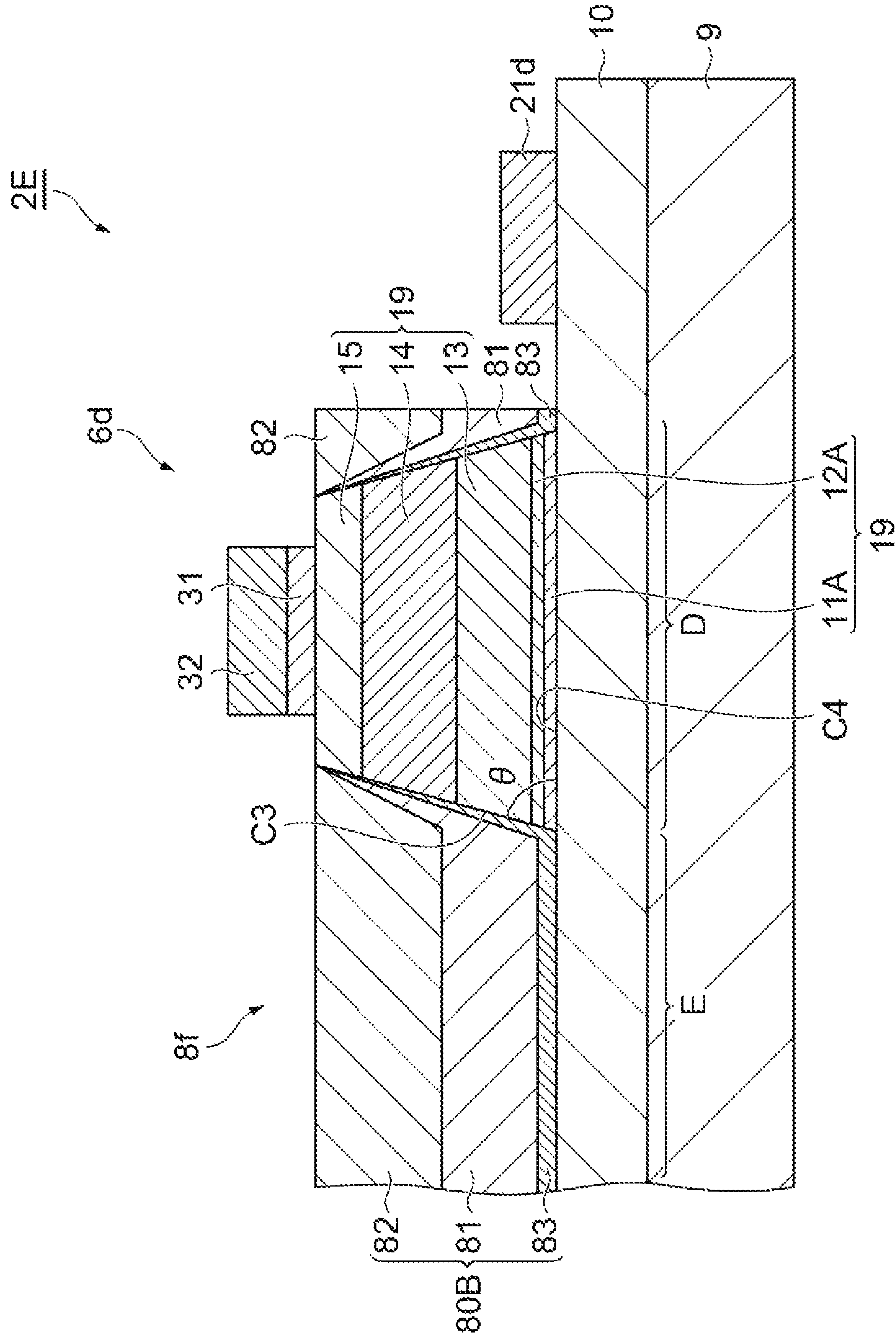

2E
6d
8f
10
9
21d
19
15
14
13
81
83
82
12A
11A
D
C4
31
32
θ
C3
E
80B
Fig.12

*Fig.13A*

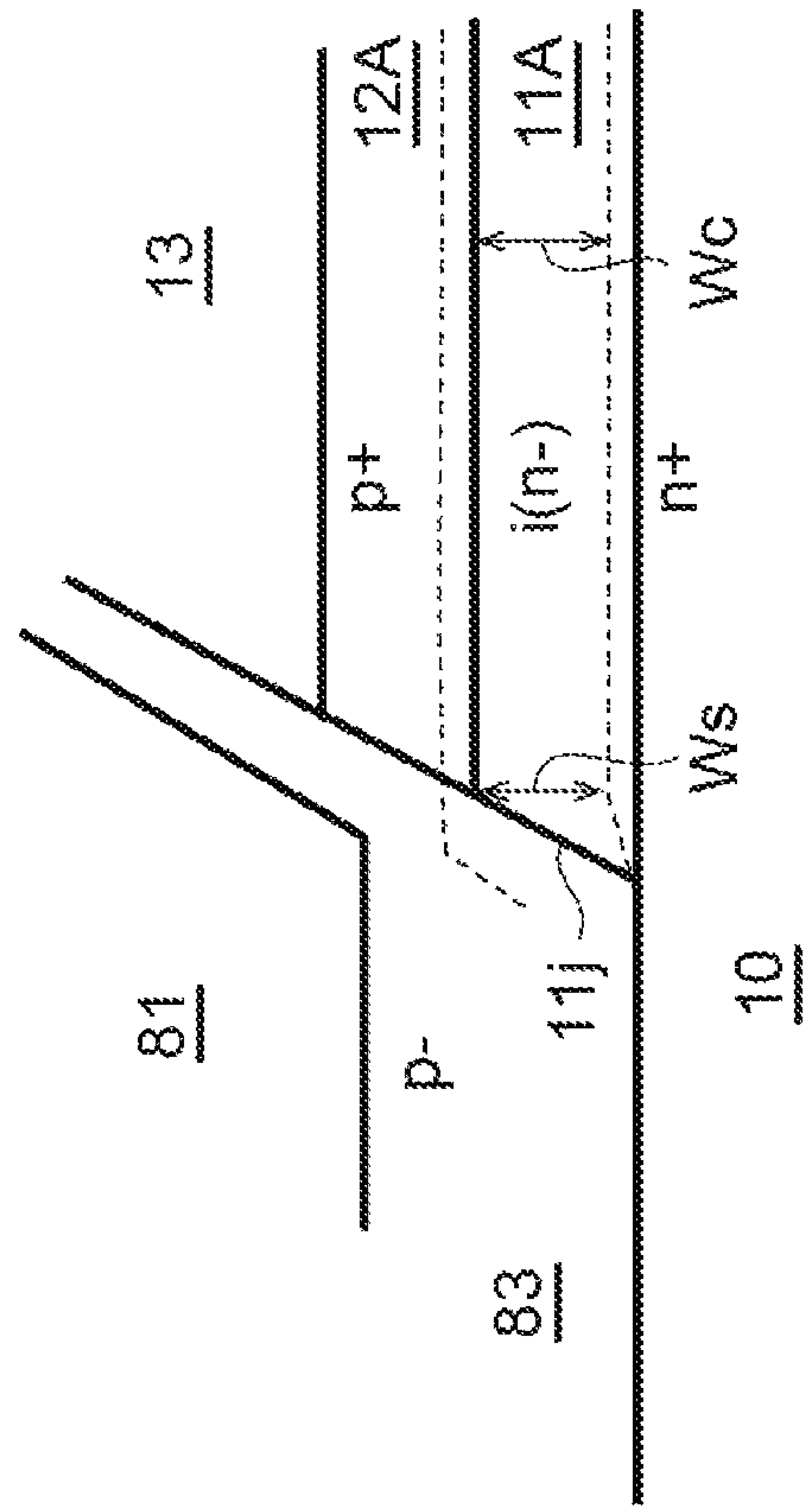



*Fig.13B*

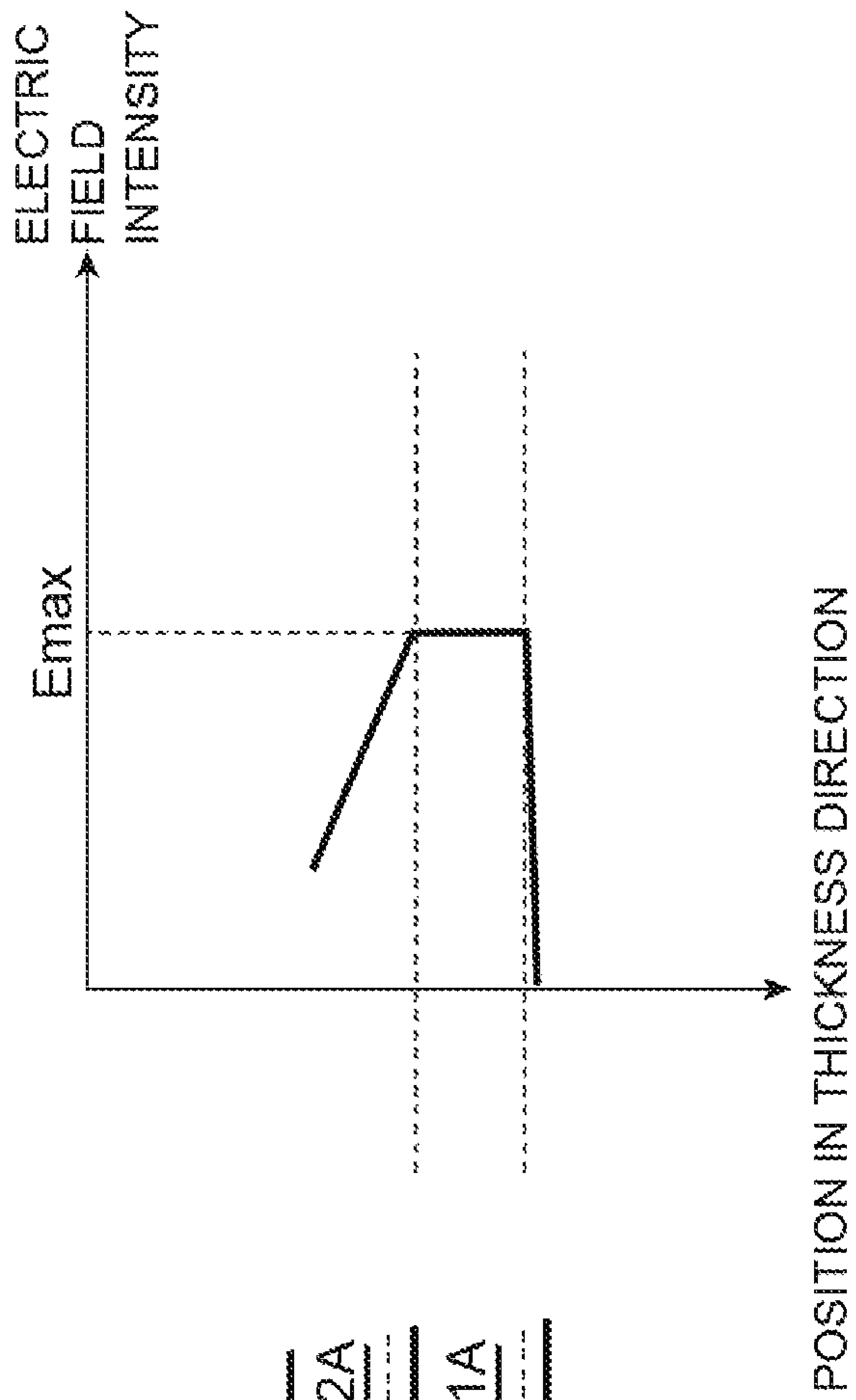
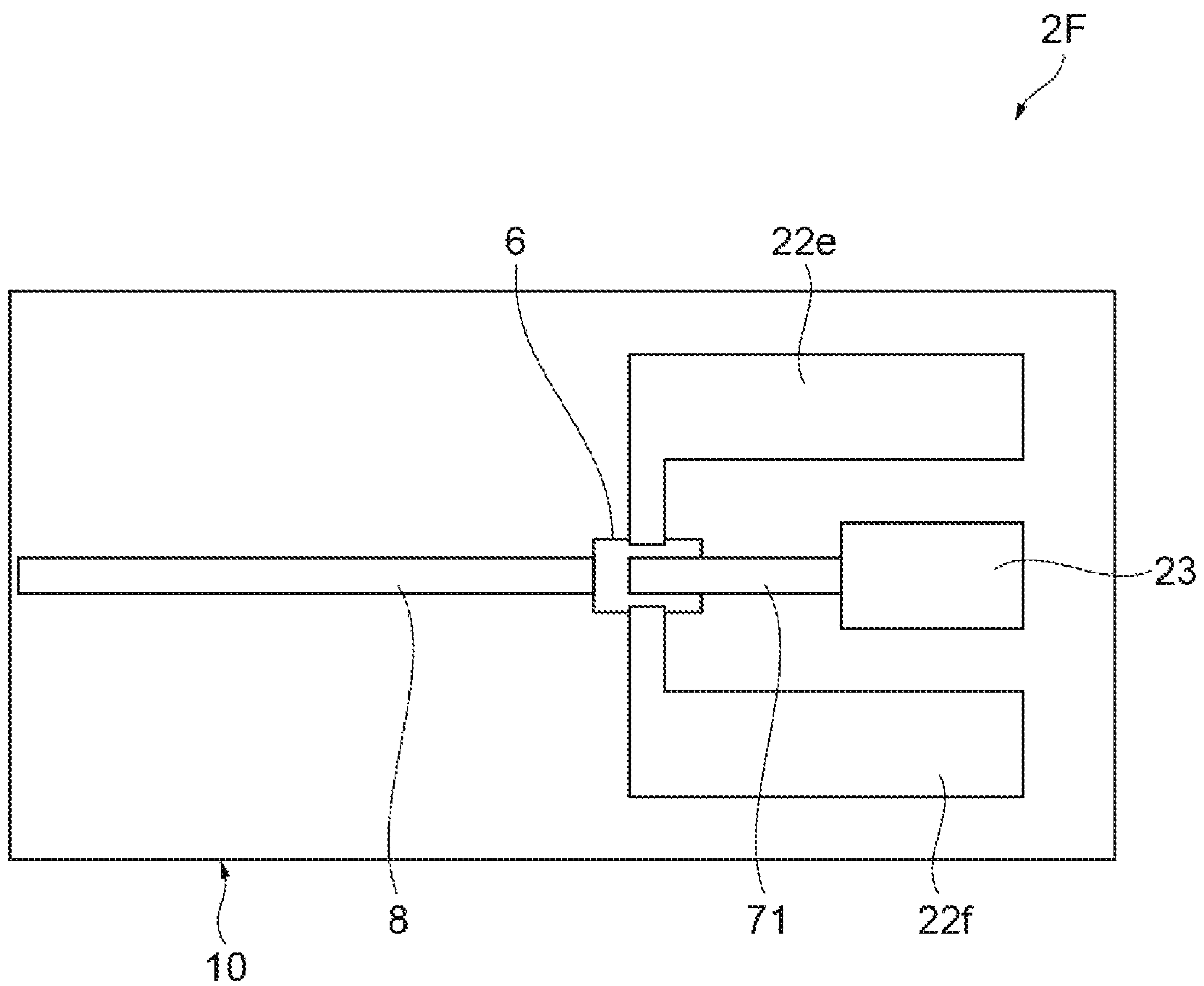


*Fig.14*



# OPTICAL WAVEGUIDE TYPE PHOTODETECTOR

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of the priority from Japanese Patent Application No. 2020-035029, filed on Mar. 2, 2020, the entire contents of which are incorporated herein by reference.

## TECHNICAL FIELD

The present disclosure relates to an optical waveguide type photodetector.

## BACKGROUND

JP2013-110207A discloses a technology related to a semiconductor optical integrated element and a method of manufacturing the same. The semiconductor optical integrated element disclosed in this literature includes a photodiode region formed on a semiconductor substrate, and an optical waveguide region subjected to butt joint coupling to an end face of the photodiode region. The photodiode region includes an optical absorption layer and a p-type cladding layer laminated in this order on an n-type cladding layer. The optical waveguide region includes an optical waveguide layer and an upper cladding layer laminated in this order on the n-type cladding layer. The optical waveguide layer has an ascending portion with respect to the inclined butt joint end face.

## SUMMARY

The present disclosure provides an optical waveguide type photodetector. The optical waveguide type photodetector includes a first semiconductor layer, a multiplication layer, an optical waveguide structure, and a waveguide type photodiode structure. The first semiconductor layer is of a first conductive type. The multiplication layer is of a first conductive type. The multiplication layer is provided on the first semiconductor layer. The optical waveguide structure has an end face. The optical waveguide structure is provided on a first region of the multiplication layer and includes an optical waveguiding core layer and a cladding layer. The waveguide type photodiode structure has an end face. The waveguide type photodiode structure is provided on a second region of the multiplication layer. The waveguide type photodiode structure has a third semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or of a second conductive type, a second semiconductor layer being of a second conductive type which are arranged in this order. The end face of the waveguide type photodiode structure and the end face of the optical waveguide structure are in contact.

The present disclosure provides an optical waveguide type photodetector. The optical waveguide type photodetector includes a first semiconductor layer, an optical waveguide structure, and a waveguide type photodiode structure. The first semiconductor layer is of a first conductive type. The optical waveguide structure has an end face. The optical waveguide structure is provided on a first region of the first semiconductor layer and includes an optical waveguiding core layer and a cladding layer. The waveguide type photodiode structure has an end face. The waveguide type photodiode structure is provided on a second region of the first semiconductor layer. The waveguide type photodiode structure has a multiplication layer being of a first conductive type, a seventh semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or a second conductive type, and a second semiconductor layer being of a second conductive type which are arranged in this order. The end face of the waveguide type photodiode structure faces to the end face of the optical waveguide structure. The sixth semiconductor layer is of a second conductive type. The sixth semiconductor layer is located between the end face of the optical waveguide structure and the end face of the waveguide type photodiode structure. The sixth semiconductor layer is contacted with the multiplication layer in the end face of the waveguide type photodiode structure.



## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a plan view illustrating a configuration of a light receiving device including an optical waveguide type photodetector according to a first embodiment.

FIG. **2** is a view illustrating a cross section along line II-II illustrated in FIG. **1**.

FIG. **3** is an enlarged cross-sectional view illustrating a part of FIG. **2**.

FIG. **4** is a view illustrating a cross section along line IV-IV illustrated in FIG. **1**.

FIG. **5** is a view illustrating a cross section along line V-V illustrated in FIG. **1**.

FIG. **6** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector as a comparative example and illustrates a cross section corresponding to line V-V in FIG. **1**.

FIG. **7**A is an enlarged view of a part in the vicinity of an end face of the multiplication layer in the comparative example.

FIG. **7**B is a view illustrating change in electric field intensity of the multiplication layer in a thickness direction.

FIG. **8**A is an enlarged view of a part in the vicinity of the end face of the multiplication layer in the first embodiment.

FIG. **8**B is a view illustrating change in electric field intensity of the multiplication layer in the thickness direction.

FIG. **9** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector according to a first modification and illustrates a cross section corresponding to line V-V in FIG. **1**.

FIG. **10** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector according to a second modification and illustrates a cross section corresponding to line V-V in FIG. **1**.

FIG. **11** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector according to a third modification and illustrates a cross section corresponding to line V-V in FIG. **1**.

FIG. **12** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector according to a second embodiment and illustrates a cross section corresponding to line V-V in FIG. **1**.

FIG. **13**A is an enlarged view of a part in the vicinity of the end face of the multiplication layer in the second embodiment.

FIG. **13**B is a view illustrating change in electric field intensity of the multiplication layer in the thickness direction.

FIG. **14** is a plan view illustrating an example of the optical waveguide type photodetector.

## DETAILED DESCRIPTION

### Problem to be Solved by Present Disclosure

In recent years, optical waveguide type photodetectors in which an optical waveguide structure and a waveguide type photodiode structure are integrated on a common substrate have been researched and developed. For example, such optical waveguide type photodetectors are used as reception front ends of an optical transmission system which has a high transmission rate such as 40 Gb/s or faster and in which a multi-level modulation method and a digital coherent reception method are combined. An optical waveguide type photodetector is produced by forming a butt joint structure constituted of a semiconductor lamination unit for a photodiode including an optical absorption layer and a semiconductor lamination unit for an optical waveguide including an optical waveguiding core layer on a substrate.

An optical waveguide type photodetector used as a reception front end of an optical transmission system may be required to have high reception sensitivity. As a solution therefor, it is conceivable to cause a waveguide type photodiode structure to have an avalanche multiplication action. In such a case, it is preferable to provide a multiplication layer for avalanche multiplication between an optical absorption layer constituting a photodiode and a semiconductor layer thereunder. However, in many cases, a butt joint interface is formed through wet etching, and thus it is inclined with respect to a direction perpendicular to a main surface of a substrate (for example, refer to JP2013-110207A). Therefore, an end face (butt joint interface) of a multiplication layer is also inclined with respect to the direction. In such a case, depletion does not proceed in parts in the vicinity of the end faces of the multiplication layer compared to other parts in the multiplication layer, and thus a depletion range of a part in the vicinity of the end face of the multiplication layer become narrow compared to depletion ranges of other parts in the multiplication layer. Hence, a maximum electric field (Emax) becomes larger in a part in the vicinity of the end face of the multiplication layer than in other parts in the multiplication layer. As a result, edge breakdown is likely to occur.

### Effects of Present Disclosure

According to an optical waveguide type photodetector of the present disclosure, a depletion range of a multiplication layer for avalanche multiplication can be made approximately uniform.

## DESCRIPTION OF EMBODIMENT OF PRESENT DISCLOSURE

First, embodiments of the present disclosure will be enumerated and described. According to an embodiment, there is provided an optical waveguide type photodetector including a first semiconductor layer, a multiplication layer, an optical waveguide structure, and a waveguide type photodiode structure. The first semiconductor layer is of a first conductive type. The multiplication layer is of a first conductive type. The multiplication layer is provided on the first semiconductor layer. The optical waveguide structure has an end face. The optical waveguide structure is provided on a first region of the multiplication layer and includes an optical waveguiding core layer and a cladding layer. The waveguide type photodiode structure has an end face. The waveguide type photodiode structure is provided on a second region of the multiplication layer. The waveguide type photodiode structure has a third semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or of a second conductive type, a second semiconductor layer being of a second conductive type which are arranged in this order. The end face of the waveguide type photodiode structure and the end face of the optical waveguide structure are in contact.

The optical waveguide type photodetector includes the multiplication layer and the third semiconductor layer. The multiplication layer is a carrier multiplication layer provided between the first semiconductor layer and the optical absorption layer. The multiplication layer is of a first conductive type or is an undoped layer. The third semiconductor layer is an electric field lowering layer provided between the multiplication layer and the optical absorption layer. The third semiconductor layer is of a second conductive type. In this manner, since the optical waveguide type photodetector includes the multiplication layer and the third semiconductor layer, a waveguide type photodiode structure having an avalanche multiplication action can be obtained. As described above, when an end face of the multiplication layer is inclined, depletion does not proceed in a part in the vicinity of the end face of the multiplication layer compared to other parts in the multiplication layer, and thus a depletion range of a part in the vicinity of the end face of the multiplication layer become narrow compared to other parts in the multiplication layer. In contrast, in this optical waveguide type photodetector, the multiplication layer and the third semiconductor layer extend between the first region of the first semiconductor layer and the optical waveguiding core layer. Hence, unevenness of the depletion range caused by inclination of the end face is reduced. That is, according to this optical waveguide type photodetector, the depletion range of the multiplication layer can be made approximately uniform from a central part to a part in the vicinity of the end face. As a result, partial increase in maximum electric field (Emax) in the multiplication layer is curbed, and edge breakdown can be made unlikely to occur.

In the foregoing optical waveguide type photodetector, the multiplication layer between the first region of the first semiconductor layer and the optical waveguiding core layer may be provided throughout an entire area of the optical waveguide structure. In such a case, when an optical waveguide type photodetector is manufactured, it is only necessary to cause the multiplication layer and the third semiconductor layer to grow on the entire surface of the first semiconductor layer, and thus manufacturing steps can be simplified.

In the foregoing optical waveguide type photodetector may further include a buffer layer of a first conductive type or being an undoped layer, and a fourth semiconductor layer of a first conductive type. The buffer layer is provided between the first semiconductor layer and the multiplication layer and has a lower impurity concentration than the first semiconductor layer. The fourth semiconductor layer is provided between the buffer layer and the multiplication layer and has a higher impurity concentration than the multiplication layer. Due to the fourth semiconductor layer, the depletion range can expand by controlling the electric field intensity of the buffer layer at the time of applying a reverse bias voltage to the extent that multiplication of carriers does not occur. Hence, a CR time constant of the photodiode (C: capacitance, and R: resistance) can be further

reduced. As a result, faster (broadband) high-frequency response characteristics can be realized.

In the foregoing optical waveguide type photodetector, the waveguide type photodiode structure may further include a fifth semiconductor layer provided between the third semiconductor layer and the optical absorption layer. A center position of the optical waveguiding core layer in a thickness direction and a center position of the optical absorption layer in the thickness direction can be accurately aligned with each other by adjusting the thickness of the fifth semiconductor layer. Hence, even when the optical absorption layer is thinned, a coupling loss between the optical absorption layer and the optical waveguiding core layer can be reduced by matching a mode field of the optical absorption layer and a mode field of the optical waveguiding core layer.

According to another embodiment, there is provided an optical waveguide type photodetector including a first semiconductor layer, an optical waveguide structure, and a waveguide type photodiode structure. The first semiconductor layer is of a first conductive type. The optical waveguide structure has an end face. The optical waveguide structure is provided on a first region of the first semiconductor layer and includes an optical waveguiding core layer and a cladding layer. The waveguide type photodiode structure has an end face. The waveguide type photodiode structure is provided on a second region of the first semiconductor layer. The waveguide type photodiode structure has a multiplication layer being of a first conductive type, a seventh semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or a second conductive type, and a second semiconductor layer being of a second conductive type which are arranged in this order. The end face of the waveguide type photodiode structure faces to the end face of the optical waveguide structure. The sixth semiconductor layer is of a second conductive type. The sixth semiconductor layer is located between the end face of the optical waveguide structure and the end face of the waveguide type photodiode structure. The sixth semiconductor layer is contacted with the multiplication layer in the end face of the waveguide type photodiode structure.

Also in this optical waveguide type photodetector, similar to the optical waveguide type photodetector described above, the optical waveguide type photodetector includes the multiplication layer and the third semiconductor layer. Accordingly, a waveguide type photodiode structure having an avalanche multiplication action can be obtained. Furthermore, in this optical waveguide type photodetector, the sixth semiconductor layer of a second conductive type is provided between the end face of the optical waveguide structure and the end face of the waveguide type photodiode structure. The sixth semiconductor layer comes into contact with the multiplication layer. In this case, at the time of applying a reverse bias, a part in the vicinity of the end face of the multiplication layer are supplemented with carriers from the sixth semiconductor layer, and thus the depletion range of a part in the vicinity of the end face of the multiplication layer expand. That is, according to this optical waveguide type photodetector, the depletion range of the multiplication layer can be made approximately uniform from a central part to a part in the vicinity of the end face. As a result, partial increase in maximum electric field (Emax) in the multiplication layer is curbed, and edge breakdown can be made unlikely to occur.

## Details of Embodiment of Present Disclosure

Specific examples of an optical waveguide type photodetector according to embodiments of the present disclosure will be described below with reference to the drawings. The present invention is not limited to the examples, but is indicated by the appended claims and is intended to include all modifications within the meaning and scope equivalent to the appended claims. In the following description, the same elements will be designated by the same reference numerals in the description of the drawings, and redundant description will be omitted. In the following description, the term "undoped" denotes that the impurity concentration is an extremely low concentration such as $1\times10^{15}$ $cm^{-3}$ or lower, for example.

An embodiment of the present disclosure relates to an avalanche photodiode (APD) used in high-speed and large capacitance optical communication systems. The embodiment of the present disclosure relates to realization of rapidity, high sensitivity performance, and high reliability using a waveguide structure. The embodiment of the present disclosure relates to a multi-channel integrated photodetector in which a 90° hybrid function used in a digital coherent optical communication system is monolithically integrated. The embodiment of the present disclosure relates to realization of high sensitivity performance and high reliability using integration of an APD structure.

## First Embodiment

FIG. **1** is a plan view illustrating a configuration of a light receiving device including an optical waveguide type photodetector according to a first embodiment of the present disclosure. FIG. **2** illustrates a cross section along line II-II illustrated in FIG. **1**, and FIG. **3** is an enlarged view illustrating a part of FIG. **2**. FIG. **4** illustrates a cross section along line IV-IV illustrated in FIG. **1**. FIG. **5** illustrates a cross section along line V-V illustrated in FIG. **1**. In FIG. **5**, illustration of insulating films **16** and **17** is omitted.

As illustrated in FIG. **1**, a light receiving device **1**A according to the present embodiment includes an optical waveguide type photodetector **2**A and signal amplification units **3**A and **3**B. The photodetector **2**A has a flat surface shape such as a substantially rectangular shape. For example, the photodetector **2**A has a substrate made of a compound semiconductor such as InP, and an optical waveguide formed on the substrate. The photodetector **2**A has two input ports **4***a* and **4***b* and an optical branching portion (optical coupler) **5**. The photodetector **2**A further has photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* formed on the substrate, and capacitor portions **7***a*, **7***b*, **7***c*, and **7***d*. That is, the photodetector **2**A has a structure in which the optical waveguide and the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* are monolithically integrated on a common substrate.

The photodetector **2**A has end edges **2***a* and **2***b* extending in a predetermined direction A. The end edge **2***a* faces the end edge **2***b* in a direction B intersecting (for example, orthogonal to) the direction A. The two input ports **4***a* and **4***b* are provided at the end edge **2***a* of the photodetector **2**A. An optical signal La is input to the input port **4***a* from outside of the light receiving device **1**A. The optical signal La includes four signal components modulated by a quadrature phase shift keying (QPSK) method. A local oscillation light Lb is input to the input port **4***b*. The input port **4***a* is optically coupled to an optical branching portion **5** via an optical waveguide portion **8***a*. The input port **4***b* is optically coupled to the optical branching portion **5** via an optical waveguide portion **8***b*. The optical waveguide portions **8***a* and **8***b* are suitably constituted of a core layer and a cladding layer. The core layer is made of a material having a relatively large refractive index (for example, InGaAsP). The cladding layer

is made of a material having a smaller refractive index (for example, InP) than the core layer and covers the core layer.

The optical branching portion **5** constitutes a 90° optical hybrid. The optical branching portion **5** is constituted of a multi-mode interference (MMI) coupler. The optical branching portion **5** causes the optical signal La and the local oscillation light Lb to interfere with each other. Accordingly, the optical signal La branches into four signal components Lc**1**, Lc**2**, Lc**3**, and Lc**4** modulated by the QPSK method. A polarization state of the signal component Lc**1** is equivalent to a polarization state of the signal component Lc**2**, and the signal component Lc**1** and the signal component Lc**2** have an in-phase relationship. A polarization state of the signal component Lc**3** is equivalent to a polarization state of the signal component Lc**4**, and the polarization states of the signal components Lc**3** and Lc**4** differ from the polarization states of the signal components Lc**1** and Lc**2**. The signal components Lc**3** and Lc**4** have a quadrature relationship.

Each of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* has a configuration as an avalanche multiplication type PIN photodiode. The photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* are disposed side by side in this order along the end edge **2***b* of the photodetector **2**A. The photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* are optically coupled to corresponding output ports of the optical branching portion **5** via optical waveguide portions **8***c*, **8***d*, **8***e*, and **8***f*, respectively. A uniform bias voltage is supplied to cathodes of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d*. Each of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* receives each of the four signal components Lc**1**, Lc**2**, Lc**3**, and Lc**4** from the optical branching portion **5** and generates an electrical signal (photoelectric current) corresponding to a light intensity of each of these signal components Lc**1**, Lc**2**, Lc**3**, and Lc**4**. Electrode pads **21***a*, **21***b*, **21***c*, and **21***d* are provided on the light receiving element **2**A for outputting signals. The electrode pads **21***a*, **21***b*, **21***c*, and **21***d* are electrically connected to anodes of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d*. The electrode pads **21***a*, **21***b*, **21***c*, and **21***d* are provided side by side in the direction A along the end edge **2***b* of the photodetector **2**A. Each of the electrode pads **21***a*, **21***b*, **21***c*, and **21***d* is electrically connected to each of electrode pads **61***a*, **61***b*, **61***c*, and **61***d* (for inputting signals) of the signal amplification units **3**A and **3**B via each of bonding wires **20***a*, **20***b*, **20***c*, and **20***d*.

The capacitor portions **7***a*, **7***b*, **7***c*, and **7***d* are so-called metal-insulator-metal (MIM) capacitors. The capacitor portions **7***a*, **7***b*, **7***c*, and **7***d* are constituted of a ground layer made of a semiconductor, a lower metal layer and an upper metal layer laminated on this ground layer, and an insulating film (the insulating film **17** illustrated in FIG. **2**) interposed between the lower metal layer and the upper metal layer. For example, each of the lower metal layer and the upper metal layer has a laminated structure such as TiW/Au or Ti/Au/Pt. The capacitor portions **7***a*, **7***b*, **7***c*, and **7***d* are disposed side by side (adjacent to each other) in the direction A with respect to the respective photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* on the photodetector **2**A. Each of the capacitor portions **7***a*, **7***b*, **7***c*, and **7***d* is electrically connected between a bias wiring for supplying a bias voltage to each of the cathodes of the photodetector portions **6***a*, **6***b*, **6***c*, or **6***d* and a reference potential wiring (GND line). An opening of the insulating film **17** is provided on a part of the lower metal layer which is not covered by the upper metal layer. A bias wiring **42** (refer to FIG. **2**) is provided on the lower metal layer exposed through the opening. The lower metal layer is electrically connected to the bias wiring **42**. The reference potential (GND) wiring is provided on the upper metal layer. The upper metal layer is electrically connected to the reference potential wiring. Due to each of the capacitor portions **7***a*, **7***b*, **7***c*, and **7***d*, an inductance component between each of the cathodes of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* and a by-pass capacitor (not illustrated) can be aligned in a design aspect.

Each of the capacitor portions **7***a*, **7***b*, **7***c*, and **7***d* has each of electrode pads **22***a*, **22***b*, **22***c*, and **22***d* (for a bias voltage) connected to the lower metal layer, and each of electrode pads **23***a*, **23***b*, **23***c*, and **23***d* (for a reference potential) connected to the upper metal layer. The electrode pads **23***a*, **23***b*, **23***c*, and **23***d* are disposed between the electrode pads **22***a*, **22***b*, **22***c*, and **22***d* and the end edge **2***b* of the photodetector **2**A in the direction B.

One end of each of bonding wires **20***i*, **20***j*, **20***k*, and **20***m* is connected to each of the electrode pads **22***a*, **22***b*, **22***c*, and **22***d*. The other end of each of the bonding wires **20***i*, **20***j*, **20***k*, and **20***m* is electrically connected to a bias voltage source (not illustrated). The bonding wires **20***i*, **20***j*, **20***k*, and **20***m* constitute parts of wirings for supplying a bias voltage to the respective photodetector portions **6***a*, **6***b*, **6***c*, and **6***d*.

One end of each of bonding wires **20***e*, **20***f*, **20***g*, and **20***h* is connected to each of the electrode pads **23***a*, **23***b*, **23***c*, and **23***d*. Each of the bonding wires **20***e*, **20***f*, **20***g*, and **20***h* is provided along each of the bonding wires **20***a*, **20***b*, **20***c*, and **20***d*. The other end of each of the bonding wires **20***e*, **20***f*, **20***g*, and **20***h* is connected to each of electrode pads **62***a*, **62***c*, **62***d*, and **62***f* for a reference potential of the signal amplification units **3**A and **3**B.

The signal amplification units **3**A and **3**B are amplifiers (trans impedance amplifiers: TIA) for amplifying an electrical signal (photoelectric current) output from the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d*. The signal amplification unit **3**A has two electrode pads **61***a* and **61***b* for inputting signals. The signal amplification unit **3**A performs differential amplification of electrical signals input to the electrode pads **61***a* and **61***b* and generates one voltage signal. The signal amplification unit **3**B has two electrode pads **61***c* and **61***d* for inputting signals. The signal amplification unit **3**B performs differential amplification of electrical signals input to the electrode pads **61***c* and **61***d* and generates one voltage signal. The electrode pads **61***a*, **61***b*, **61***c*, and **61***d* are disposed side by side in this order along the end edge **2***b* of the photodetector **2**A and in the direction A. As described above, each of the electrode pads **61***a*, **61***b*, **61***c*, and **61***d* is electrically connected to each of the electrode pads **21***a*, **21***b*, **21***c*, and **21***d* via each of the bonding wires **20***a*, **20***b*, **20***c*, and **20***d*.

The signal amplification unit **3**A further has three electrode pads **62***a*, **62***b*, and **62***c*. The electrode pads **62***a*, **62***b*, and **62***c* are disposed side by side in this order along the end edge **2***b* of the photodetector **2**A and in the direction A. The electrode pad **61***a* is disposed between the electrode pads **62***a* and **62***b*. The electrode pad **61***b* is disposed between the electrode pads **62***b* and **62***c*. Similarly, the signal amplification unit **3**B further has three electrode pads **62***d*, **62***e*, and **62***f*. The electrode pads **62***d*, **62***e*, and **62***f* are disposed side by side in this order along the end edge **2***b* of the photodetector **2**A and in the direction A. The electrode pad **61***c* is disposed between the electrode pads **62***d* and **62***e*. The electrode pad **61***d* is disposed between the electrode pads **62***e* and **62***f*. As described above, each of the electrode pads **62***a*, **62***c*, **62***d*, and **62***f* of the signal amplification units **3**A and **3**B is electrically connected to each of the electrode pads **23***a*, **23***b*, **23***c*, and **23***d* via each of the bonding wires **20***e*, **20***f*, **20***g*, and **20***h*.

FIG. **2** illustrates cross-sectional structures of two photodetector portions **6***c* and **6***d* of the four photodetector portions **6***a*, **6***b*, **6***c*, and **6***d*. FIG. **3** illustrates a cross-sectional structure of the photodetector portion **6***d*. The remaining photodetector portions **6***a* and **6***b* have a cross-sectional structure similar to this. FIG. **4** illustrates a cross-sectional structure of one optical waveguide portion **8***f* of six optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f*. The remaining optical waveguide portions **8***a* to **8***e* also have a cross-sectional structure similar to this. FIG. **5** illustrates a cross-sectional structure of a joint part between the photodetector portion **6***d* and the optical waveguide portion **8***f*. A joint part between the photodetector portion **6***a* and the optical waveguide portion **8***c*, a joint part between the photodetector portion **6***b* and the optical waveguide portion **8***d*, and a joint part between the photodetector portion **6***c* and the optical waveguide portion **8***e* also have a cross-sectional structure similar to this.

As illustrated in FIG. **5**, the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* and the optical waveguide portions **8***c*, **8***d*, **8***e*, and **8***f* are integrated on a common substrate **9**. For example, the substrate **9** is a semi-insulating InP substrate. The cross-sectional structures of the photodetector portions **6***a*, **6***b*, **6***c*, and **6***d* will be described by taking the photodetector portion **6***d* as an example. As illustrated in FIG. **3**, the photodetector portion **6***d* has an n-type semiconductor layer **10** and a waveguide type photodiode structure **19**. The n-type semiconductor layer **10** is provided on the substrate **9** and is of a high-concentration n-type conductive type. The photodiode structure **19** is provided on a region D (a second region, refer to FIG. **5**) of the n-type semiconductor layer **10**.

The photodiode structure **19** has an optical absorption layer **13**, a p-type semiconductor layer **14**, and a p-type contact layer **15**. The optical absorption layer **13** is provided on the n-type semiconductor layer **10**. The p-type semiconductor layer **14** is provided on the optical absorption layer **13** and is of a p-type conductive type. The p-type contact layer **15** is provided on the p-type semiconductor layer **14** and is of a p-type conductive type. Moreover, the photodiode structure **19** has a multiplication layer **11** and a p-type electric field control layer **12**. The multiplication layer **11** is provided between the n-type semiconductor layer **10** and the optical absorption layer **13**. The p-type electric field control layer **12** is provided between the multiplication layer **11** and the optical absorption layer **13**. The n-type semiconductor layer **10** is a first semiconductor layer according to the present embodiment. The p-type semiconductor layer **14** is a second semiconductor layer according to the present embodiment. The p-type electric field control layer **12** is a third semiconductor layer according to the present embodiment.

The n-type semiconductor layer **10** comes into ohmic contact with an n-type ohmic electrode **41** (refer to FIG. **3**). For example, the n-type semiconductor layer **10** is a Si-doped InP layer. For example, a Si-doping concentration of the n-type semiconductor layer **10** is $1\times10^{17}$ $cm^{-3}$ or higher. For example, a thickness of the n-type semiconductor layer **10** is within a range of 1 μm to 2 μm. The multiplication layer **11** is an electron injection type carrier multiplication layer. The multiplication layer **11** is of an i-type (undoped) conductive type or an n-type conductive type having a lower impurity concentration than the n-type semiconductor layer **10**. For example, the multiplication layer **11** is a Si-doped InAlAs layer. For example, a Si-doping concentration of the multiplication layer **11** is $3\times10^{16}$ $cm^{-3}$ or lower. For example, a thickness of the multiplication layer **11** is within a range of 0.050 μm to 0.200 μm. The p-type electric field control layer **12** is a layer provided to lower an electric field of the optical absorption layer **13**. The p-type electric field control layer **12** is of a p-type conductive type having a higher impurity concentration than the optical absorption layer **13**. For example, the p-type electric field control layer **12** is a Zn-doped InP layer or a Zn-doped InAlGaAs layer. For example, a Zn-doping concentration of the p-type electric field control layer **12** is $1\times10^{18}$ $cm^{-3}$ or higher. For example, a thickness of the p-type electric field control layer **12** is within a range of 0.025 μm to 0.100 μm.

For example, the optical absorption layer **13** is an undoped InGaAs layer or a low-concentration p-type InGaAs layer of which the Zn-doping concentration is $3\times10^{16}$ $cm^{-3}$ or lower. For example, a thickness of the optical absorption layer **13** is within a range of 0.1 μm to 0.4 μm. For example, the p-type semiconductor layer **14** is a Zn-doped InP layer. For example, a Zn-doping concentration of the p-type semiconductor layer **14** is $2\times10^{17}$ $cm^{-3}$ or higher. For example, a thickness of the p-type semiconductor layer **14** is within a range of 1 μm to 2.5 μm. For example, the p-type contact layer **15** is a Zn-doped InGaAs layer. For example, a Zn-doping concentration of the p-type contact layer **15** is $1\times10^{18}$ $cm^{-3}$ or higher. For example, a thickness of the p-type contact layer **15** is within a range of 0.1 μm to 0.3 μm.

A composition graded layer may be provided between the optical absorption layer **13** and the p-type semiconductor layer **14** for alleviating hetero-energy barriers (ΔEv and ΔEc) between both layers. This composition graded layer is of an undoped conductive type or a p-type conductive type of which the Zn-doping concentration is $1\times10^{17}$ $cm^{-3}$ or lower. A p-type hetero-barrier alleviation layer may be provided between the p-type semiconductor layer **14** and the p-type contact layer **15**. For example, this hetero-barrier alleviation layer is constituted of two Zn-doped InGaAsP layers of which the doping concentration is $1\times10^{18}$ $cm^{-3}$ or higher. For example, bandgap wavelengths of the two Zn-doped InGaAsP layers are 1.1 μm and 1.3 μm, respectively.

A part of the n-type semiconductor layer **10**, the multiplication layer **11**, the p-type electric field control layer **12**, the optical absorption layer **13**, the p-type semiconductor layer **14**, and the p-type contact layer **15** constitute a stripe mesa structure extending in a predetermined optical waveguiding direction (the direction B of FIG. **1** in the present embodiment). The stripe mesa structure has a pair of side surfaces. The pair of side surfaces of this stripe mesa structure are embedded by an embedment region **18**. For example, the embedment region **18** is formed of a semi-insulating material such as Fe-doped InP. For example, a width of the stripe mesa structure in a direction orthogonal to the optical waveguiding direction (the direction A in FIG. **1**) is within a range of 1.5 μm to 3 μm. For example, a height of the stripe mesa structure is within a range of 2 μm to 3.5 μm.

The photodetector portion **6***d* further has the insulating films **16** and **17**. The insulating films **16** and **17** are provided from an upper surface of the stripe mesa structure to a part on the embedment region **18**. The insulating films **16** and **17** cover and protect the upper surface of the stripe mesa structure and the embedment region **18**. For example, the insulating films **16** and **17** are films made of an insulating silicon compound such as SiN, SiON, or $SiO_2$. The insulating films **16** and **17** have an opening on the upper surface of the stripe mesa structure. A p-type ohmic electrode **31** is provided on the p-type contact layer **15** exposed from the insulating films **16** and **17** through the openings.

For example, the p-type ohmic electrode **31** is made of an alloy of AuZn or Pt and the p-type contact layer **15**. A wiring **32** is provided on the p-type ohmic electrode **31**. The wiring **32** extends in the optical waveguiding direction (the direction B in FIG. **1**) and electrically connects the p-type ohmic electrode **31** and the electrode pad **21***d* to each other. For example, the wiring **32** has a laminated structure such as TiW/Au or Ti/Pt/Au. For example, the electrode pad **21***d* is formed through Au plating.

The insulating films **16** and **17** also have another opening on the n-type semiconductor layer **10** separated from the mesa structure of the photodetector portion **6***d*. The n-type ohmic electrode **41** serving as a cathode is provided on the n-type semiconductor layer **10** exposed from the insulating films **16** and **17** through the openings. For example, the n-type ohmic electrode **41** is made of an alloy of AuGe or AuGeNi and the n-type semiconductor layer **10**. A bias wiring **42** is provided on the n-type ohmic electrode **41**. The bias wiring **42** extends to the lower metal layer of the capacitor portion **7***d* and electrically connects the lower metal layer and the n-type ohmic electrode **41** to each other.

The capacitor portion **7***d* has the insulating film **16**, the lower metal layer, the insulating film (interlayer film) **17**, and the upper metal layer laminated in this order on the substrate **9**. For example, the upper metal layer and the lower metal layer are constituted of a laminated structure such as TiW/Au or Ti/Au/Pt. On a part of the lower metal layer which is not covered by the upper metal layer, an opening is formed in the insulating film **17**. The bias wiring **42** is provided on the lower metal layer exposed through the opening. The bias wiring **42** extends in a direction in which it becomes farther from the end edge **2***b* of the photodetector **2**A in the optical waveguiding direction (the direction B in FIG. **1**) and electrically connects the lower metal layer and the electrode pad **22***d* to each other. A wiring connected to the electrode pad **23***d* is provided on the upper metal layer. This wiring extends in a direction in which it becomes closer to the end edge **2***b* of the photodetector **2**A in the optical waveguiding direction and electrically connects the upper metal layer and the electrode pad **23***d* to each other.

A via **51** is provided on the substrate **9**. The via **51** is a metal conductive material and is formed through Au plating, for example. The via **51** is provided in a manner of penetrating the substrate **9** from a front surface to a rear surface. The upper metal layer of the capacitor portion **7***d* is electrically connected to one end of the via **51** on the front surface side via the electrode pad **23***d*. The other end of the via **51** on the rear surface side is connected to the reference potential line (ground potential line) shared between the signal amplification units **3**A and **3**B.

For example, the wiring connected to the electrode pad **23***d*, and the bias wiring **42** have a laminated structure such as TiW/Au or Ti/Au/Pt. For example, the electrode pad **23***d* and the electrode pad **22***d* are formed through Au plating.

Subsequently, a cross-sectional structure of the optical waveguide portion will be described. As illustrated in FIGS. **4** and **5**, the optical waveguide portion **8***f* includes the n-type semiconductor layer **10** and an optical waveguide structure **80**. The n-type semiconductor layer **10** is provided on the substrate **9**. The optical waveguide structure **80** is provided on a region E (first region) of the n-type semiconductor layer **10**. The region E is adjacent to the region D of the n-type semiconductor layer **10** in the optical waveguiding direction (the direction B in FIG. **1**). The optical waveguide structure **80** includes an optical waveguiding core layer **81** provided on the n-type semiconductor layer **10**, and a cladding layer **82** provided on the optical waveguiding core layer **81**. Moreover, the optical waveguide portion **8***f* includes the multiplication layer **11** and the p-type electric field control layer **12** provided between the n-type semiconductor layer **10** and the optical waveguide structure **80**.

The n-type semiconductor layer **10** is in common with the n-type semiconductor layer **10** of the photodetector portion **6***d* and functions as a lower cladding layer in the optical waveguide portion **8***f*. The n-type semiconductor layer **10** is provided from the photodetector portion **6***d* to the optical waveguide portion **8***f* on the substrate **9**. Similarly, the multiplication layer **11** on a region E is shared by the multiplication layer **11** of the photodetector portion **6***d*, and the p-type electric field control layer **12** on a region E is shared by the p-type electric field control layer **12** of the photodetector portion **6***d*. The multiplication layer **11** and the p-type electric field control layer **12** extend from between the region D of the n-type semiconductor layer **10** and the optical absorption layer **13** to a part between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. In the present embodiment, the multiplication layer **11** and the p-type electric field control layer **12** between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81** are provided throughout an entire area of the optical waveguide structure **80** (that is, an entire area of the optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f* viewed in the lamination direction). The composition, the doping concentration, and the thickness of the n-type semiconductor layer **10**, the multiplication layer **11**, and the p-type electric field control layer **12** in the optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f* are the same as those of the photodetector portion **6***d*.

As illustrated in FIG. **5**, the optical waveguide portion **8***f* is subjected to butt joint coupling to the photodetector portion **6***d*, and the optical waveguiding core layer **81** comes into contact with the optical absorption layer **13**. Accordingly, the optical waveguiding core layer **81** is optically coupled to the optical absorption layer **13**. For example, a butt joint interface is formed through wet etching. Hence, the butt joint interface is inclined with respect to a direction perpendicular to an upper surface **10***a* of the n-type semiconductor layer **10**, that is, an interface between the n-type semiconductor layer **10** and the multiplication layer **11**. In other words, when an interface between the optical waveguide structure **80** and the photodiode structure **19** is a first interface C**1** and an interface between the region D of the n-type semiconductor layer **10** and the photodiode structure **19** is a second interface C**2**, an angle θ formed by the first interface C**1** and the second interface C**2** is smaller than 90°. For example, the angle θ formed by the first interface C**1** and the second interface C**2** is within a range of 25° to 60°.

The optical waveguiding core layer **81** has a larger refractive index than the n-type semiconductor layer **10** and is formed of a material which can be subjected to lattice matching with the n-type semiconductor layer **10**. For example, the optical waveguiding core layer **81** is made of InGaAsP. For example, a bandgap wavelength of InGaAsP of the optical waveguiding core layer **81** is 1.05 μm. For example, a thickness of the optical waveguiding core layer **81** is within a range of 0.3 μm to 0.5 μm. The cladding layer **82** has a smaller refractive index than the optical waveguiding core layer **81** and is formed of a material which can be subjected to lattice matching with the optical waveguiding core layer **81**. For example, the cladding layer **82** is made of undoped InP. For example, a thickness of the cladding layer **82** is within a range of 1 μm to 3 μm. A height of an upper surface of the cladding layer **82** is aligned with a height of an upper surface of the p-type contact layer **15**. As illustrated

in FIG. **4**, a part of the n-type semiconductor layer **10**, the multiplication layer **11**, the p-type electric field control layer **12**, the optical waveguiding core layer **81**, and the cladding layer **82** constitute a mesa structure extending in the optical waveguiding direction (the direction B in FIG. **1**). An optical signal is confined inside the optical waveguiding core layer **81** due to this mesa structure and a difference between refractive indices of the n-type semiconductor layer **10**, the cladding layer **82**, and the optical waveguiding core layer **81**. So that the optical signal can be propagated to the photodetector portion **6***d*. The side surfaces and the upper surface of this stripe mesa structure are protected by being covered by the two insulating films **16** and **17**.

Effects obtained by the photodetector **2**A of the present embodiment having the foregoing configuration will be described. In the photodetector **2**A, the photodiode structure **19** includes the multiplication layer **11** and the p-type electric field control layer **12**. The multiplication layer **11** is a carrier multiplication layer provided between the n-type semiconductor layer **10** and the optical absorption layer **13**. The multiplication layer **11** is of an n-type conductive type having a lower impurity concentration than the n-type semiconductor layer **10** or is an undoped layer. The p-type electric field control layer **12** is an electric field lowering layer provided between the multiplication layer **11** and the optical absorption layer **13** and has a higher impurity concentration than the optical absorption layer **13**. Since the photodiode structure **19** includes the multiplication layer **11** and the p-type electric field control layer **12** described above, the photodiode structure **19** having an avalanche multiplication action can be obtained.

FIG. **6** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector **102** as a comparative example and illustrates a cross section corresponding to line V-V in FIG. **1**. The optical waveguide type photodetector **102** has a multiplication layer **11**A for avalanche multiplication and a p-type electric field control layer **12**A between the optical absorption layer **13** constituting the photodiode structure **19** and the n-type semiconductor layer **10** thereunder. The multiplication layer **11**A and the p-type electric field control layer **12**A are provided in only the photodetector portion and are not provided in the optical waveguide portion.

In many cases, since the butt joint interface is formed through wet etching, it becomes a forward mesa structure and is inclined to the photodiode side with respect to a direction perpendicular to a main surface of the substrate **9**. Therefore, an end face of the multiplication layer **11**A are also inclined in a similar manner. FIG. **7**A is an enlarged view of a part in the vicinity of the end face of the multiplication layer **11**A in such a case. A region surrounded by the dotted line in the diagram shows a depleted region. When a end face **11***j* of the multiplication layer **11**A is inclined, a length of an interface between the p-type electric field control layer **12**A and the multiplication layer **11**A in the optical waveguiding direction becomes shorter than a length of an interface between the n-type semiconductor layer **10** and the multiplication layer **11**A in the same direction in accordance with an inclination angle thereof. Hence, when a reverse bias is applied, negative electric charges become insufficient in a region in the vicinity of the end face **11***j* of the multiplication layer **11**A. As a result, depletion does not proceed compared to other parts in the multiplication layer **11**A, and a depletion range Ws of the part becomes narrow compared to a depletion range Wc of other parts in the multiplication layer **11**A.

FIG. **7**B is a view illustrating change in electric field intensity in the thickness direction. The graph G**11** shows change in electric field intensity of a part in the vicinity of the end face **11***j* of the multiplication layer **11**A. The graph G**12** shows change in electric field intensity of other parts in the multiplication layer **11**A. As illustrated in FIG. **7**B, due to the relationship between the foregoing depletion ranges Ws and Wc, a maximum electric field Emax**1** in a part in the vicinity of the end face **11***j* of the multiplication layer **11**A becomes larger than a maximum electric field Emax**2** of other parts in the multiplication layer **11**A. Therefore, edge breakdown is likely to occur in the butt joint interface. Furthermore, a multiplication current is concentrated in a part in the vicinity of the end face **11***j*, and thus reliability deteriorates.

In the photodetector **2**A of the present embodiment, the multiplication layer **11** and the p-type electric field control layer **12** extend from between the region D of the n-type semiconductor layer **10** and the optical absorption layer **13** to a part between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. FIG. **8**A is an enlarged view of a part in the vicinity of the end face of the multiplication layer **11** in such a case. A region surrounded by the dotted line in the diagram shows a depleted region. When the multiplication layer **11** and the p-type electric field control layer **12** extend between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**, as illustrated in the diagram, a difference between a length of an interface between the p-type electric field control layer **12** and the multiplication layer **11** in the optical waveguiding direction and a length of the interface between the n-type semiconductor layer **10** and the multiplication layer **11** in the same direction is resolved. Hence, the depletion range is made approximately uniform to the butt joint interface, and unevenness of the depletion range caused by inclination of the end face **11***j* is reduced. That is, according to the photodetector **2**A of the present embodiment, the depletion range of the multiplication layer **11** can be made approximately uniform.

FIG. **8**B is a view illustrating change in electric field intensity of the multiplication layer **11** in the thickness direction. According to the present embodiment, a maximum electric field Emax in the vicinity of the end face **11***j* of the multiplication layer **11** becomes equivalent to a maximum electric field of other parts in the multiplication layer **11**.

That is, partial increase in maximum electric field Emax in the multiplication layer **11** can be curbed. Therefore, edge breakdown can be made unlikely to occur. Furthermore, deterioration in reliability due to concentration of a multiplication current can be avoided.

As in the present embodiment, the multiplication layer **11** and the p-type electric field control layer **12** between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81** may be provided throughout the entire area of the optical waveguide structure **80**. In such a case, when the photodetector **2**A is manufactured, it is only necessary to cause the multiplication layer **11** and the p-type electric field control layer **12** to grow on the entire surface of the n-type semiconductor layer **10**, and thus manufacturing steps can be simplified.

(First Modification)

FIG. **9** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector **2**B according to a first modification of the foregoing embodiment and illustrates a cross section corresponding to line V-V in FIG. **1**. In addition to the configuration of the photodetector **2**A of

foregoing embodiment, the photodetector **2**B further includes a buffer layer **111** and an n-type electric field control layer **112**.

The buffer layer **111** is provided between the n-type semiconductor layer **10** and the multiplication layer **11**. The buffer layer **111** extends from a part on the region D of the n-type semiconductor layer **10** to a part on the region E of the n-type semiconductor layer **10**. The buffer layer **111** is of an n-type conductive type having a lower impurity concentration than the n-type semiconductor layer **10** or is an undoped layer. For example, the buffer layer **111** is a Si-doped InP layer. For example, a Si-doping concentration of the buffer layer **111** is $1\times10^{16}$ $cm^{-3}$ or lower. For example, a thickness of the buffer layer **111** is within a range of 0.050 μm to 0.200 μm. In the optical waveguide portion, the buffer layer **111** functions as a second lower cladding layer.

The n-type electric field control layer **112** is a layer provided to lower an electric field of the buffer layer **111**. The n-type electric field control layer **112** is a fourth semiconductor layer in the present modification. The n-type electric field control layer **112** is provided between the buffer layer **111** and the multiplication layer **11**. The n-type electric field control layer **112** extends together with the buffer layer **111** from a part on the region D of the n-type semiconductor layer **10** to a part on the region E of the n-type semiconductor layer **10**. The impurity concentration of the n-type electric field control layer **112** is higher than that of the multiplication layer **11**, for example, is $1\times10^{18}$ $cm^{-3}$ or higher. For example, the n-type electric field control layer **112** is a Si-doped InP layer.

In the present modification, due to the n-type electric field control layer **112**, the depletion range can expand by controlling the electric field intensity of the buffer layer **111** at the time of applying a reverse bias voltage to the extent that multiplication of carriers does not occur. Hence, a CR time constant of the photodetector portion can be further reduced. As a result, faster (broadband) high-frequency response characteristics can be realized.

(Second Modification)

FIG. **10** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector **2**C according to a second modification of the foregoing embodiment and illustrates a cross section corresponding to line V-V in FIG. **1**. In addition to the configuration of the photodetector **2**A of foregoing embodiment, the photodetector **2**C further includes a hetero-barrier alleviation layer **113**. The hetero-barrier alleviation layer **113** is a fifth semiconductor layer in the present modification. The hetero-barrier alleviation layer **113** is provided only between the p-type electric field control layer **12** and the optical absorption layer **13** on the region D of the n-type semiconductor layer **10** and does not extend to a part on the region E of the n-type semiconductor layer **10**. The hetero-barrier alleviation layer **113** is provided to alleviate the hetero-energy barrier between the p-type electric field control layer **12** and the optical absorption layer **13**.

The hetero-barrier alleviation layer **113** is of a p-type conductive type having a lower impurity concentration than the p-type electric field control layer **12** or is an undoped layer. A bandgap of the hetero-barrier alleviation layer **113** is between a bandgap of the p-type electric field control layer **12** and a bandgap of the optical absorption layer **13**. For example, the hetero-barrier alleviation layer **113** is a Zn-doped InGaAsP layer. For example, a bandgap wavelength of the hetero-barrier alleviation layer **113** is 1.25 μm or 1.40 μm. Alternatively, the hetero-barrier alleviation layer **113** may be a composition graded layer in which the bandgap wavelength continuously varies. For example, a Si-doping concentration of the hetero-barrier alleviation layer **113** is $1\times10^{17}$ $cm^{-3}$ or lower. For example, a thickness of the hetero-barrier alleviation layer **113** is within a range of 0.025 μm to 0.100 μm.

In the present modification, a center position of the optical absorption layer **13** in the thickness direction can be accurately aligned with a center position of the optical waveguiding core layer **81** in the thickness direction by adjusting a thickness of the hetero-barrier alleviation layer **113**. Hence, even when the optical absorption layer **13** is thinned to increase the operating speed of the photodetector **2**C, a coupling loss between the optical absorption layer **13** and the optical waveguiding core layer **81** can be reduced by matching a mode field of the optical absorption layer **13** and a mode field of the optical waveguiding core layer **81**. As a result, both reduction of a coupling loss and high sensitivity can be achieved.

(Third Modification)

FIG. **11** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector **2**D according to a third modification of the foregoing embodiment and illustrates a cross section corresponding to line V-V in FIG. **1**. The photodetector **2**D has a configuration in which the electron injection type multiplication layer **11** of the foregoing embodiment is changed to a hole injection type multiplication layer **11**C. Except for the points which will be described below, a configuration of the photodetector **2**D is similar to that of the photodetector **2**A of foregoing embodiment.

The photodetector portion ***6d*** of the photodetector **2**D has a p-type semiconductor layer **101** and a waveguide type photodiode structure **117**. The p-type semiconductor layer **101** is provided on the substrate **9** and is of a high-concentration p-type conductive type. The photodiode structure **117** is provided on the region D of the p-type semiconductor layer **101**. The photodiode structure **117** has an optical absorption layer **114** provided on the p-type semiconductor layer **101**, an n-type semiconductor layer **115** of an n-type conductive type provided on the optical absorption layer **114**, and an n-type contact layer **116** provided on the n-type semiconductor layer **115**. Moreover, the photodiode structure **117** has the multiplication layer **11**C and an n-type electric field control layer **12**C. The multiplication layer **11**C is provided between the p-type semiconductor layer **101** and the optical absorption layer **114**. The n-type electric field control layer **12**C is provided between the multiplication layer **11**C and the optical absorption layer **114**. The p-type semiconductor layer **101** is a first semiconductor layer according to the present embodiment. The n-type semiconductor layer **115** is a second semiconductor layer according to the present embodiment. The n-type electric field control layer **12**C is a third semiconductor layer according to the present embodiment.

The p-type semiconductor layer **101** comes into ohmic contact with an p-type ohmic electrode (not illustrated). For example, the p-type semiconductor layer **101** is a Zn-doped InP layer. For example, a Zn-doping concentration of the p-type semiconductor layer **101** is $1\times10^{18}$ $cm^{-3}$ or higher. For example, a thickness of the p-type semiconductor layer **101** is within a range of 1 μm to 2 μm. The multiplication layer **11**C is a hole injection type carrier multiplication layer and is of an i-type (undoped) conductive type. For example, the multiplication layer **11**C is an undoped InP layer. For example, a thickness of the multiplication layer **11**C is within a range of 0.050 μm to 0.200 μm. The n-type electric field control layer **12**C is provided to lower an electric field of the optical absorption layer **114**. The n-type electric field

control layer **12**C is of an n-type conductive type having a higher impurity concentration than the optical absorption layer **114**. For example, the n-type electric field control layer **12**C is a Si-doped InP layer or a Si-doped InAlGaAs layer. For example, a Si-doping concentration of the n-type electric field control layer **12**C is $1\times10^{18}$ $cm^{-3}$ or higher. For example, a thickness of the n-type electric field control layer **12**C is within a range of 0.025 μm to 0.100 μm.

For example, the optical absorption layer **114** is an undoped InGaAs layer or a low-concentration n-type InGaAs layer of which the Si-doping concentration is $3\times10^{16}$ $cm^{-3}$ or lower. For example, a thickness of the optical absorption layer **114** is within a range of 0.1 μm to 0.4 μm. For example, the n-type semiconductor layer **115** is a Si-doped InP layer. For example, a Si-doping concentration of the n-type semiconductor layer **115** is $2\times10^{17}$ $cm^{-3}$ or higher. For example, a thickness of the n-type semiconductor layer **115** is within a range of 1 μm to 2.5 μm. For example, the n-type contact layer **116** is a Si-doped InGaAs layer. For example, a Si-doping concentration of the n-type contact layer **116** is $1\times10^{18}$ $cm^{-3}$ or higher. For example, a thickness of the n-type contact layer **116** is within a range of 0.1 μm to 0.3 μm. An n-type ohmic electrode **131** is provided on the n-type contact layer **116**.

A composition graded layer may be provided between the optical absorption layer **114** and the n-type semiconductor layer **115** for alleviating hetero-energy barriers (ΔEv and ΔEc) between both layers. The composition graded layer is of an undoped conductive type or an n-type conductive type of which the Si-doping concentration is $1\times10^{17}$ $cm^{-3}$ or lower. An n-type hetero-barrier alleviation layer may be provided between the n-type semiconductor layer **115** and the n-type contact layer **116**. For example, the hetero-barrier alleviation layer is constituted of two Si-doped InGaAsP layers of which the doping concentration is $1\times10^{18}$ $cm^{-3}$ or higher. For example, bandgap wavelengths of the two Si-doped InGaAsP layers are 1.1 μm and 1.3 μm, respectively.

A part of the p-type semiconductor layer **101**, the multiplication layer **11**C, the n-type electric field control layer **12**C, the optical absorption layer **114**, the n-type semiconductor layer **115**, and the n-type contact layer **116** constitute a stripe mesa structure extending in the optical waveguiding direction. The stripe mesa structure has a pair of side surfaces. The pair of side surfaces of the stripe mesa structure are embedded by the embedment region **18** (refer to FIG. **3**). For example, the embedment region **18** is formed of a semi-insulating material such as Fe-doped InP.

For example, the n-type ohmic electrode **131** is made of an alloy of AuZn or Pt and the n-type contact layer **116**. A wiring **132** is provided on the n-type ohmic electrode **131**. The wiring **132** extends in the optical waveguiding direction and electrically connects the n-type ohmic electrode **131** and the electrode pad **21***d* to each other. For example, the wiring **132** has a laminated structure such as TiW/Au or Ti/Pt/Au.

The p-type semiconductor layer **101** is provided from the photodetector portion **6***d* to the optical waveguide portion **8***f* on the substrate **9**. The multiplication layer **11**C on the region E is in common with the multiplication layer **11**C of the photodetector portion **6***d*. The n-type electric field control layer **12**C on the region E is in common with the n-type electric field control layer **12**C of the photodetector portion **6***d*. The multiplication layer **11**C and the n-type electric field control layer **12**C extend from between the region D of the p-type semiconductor layer **101** and the optical absorption layer **114** to a part between the region E of the p-type semiconductor layer **101** and the optical waveguiding core layer **81**. Also in the present embodiment, the multiplication layer **11**C and the n-type electric field control layer **12**C between the region E of the p-type semiconductor layer **101** and the optical waveguiding core layer **81** are provided throughout the entire area of the optical waveguide structure **80** (that is, the entire area of the optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f* viewed in the lamination direction). The composition, the doping concentration, and the thickness of the p-type semiconductor layer **101**, the multiplication layer **11**C, and the n-type electric field control layer **12**C in the optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f* are the same as those of the photodetector portion **6***d*.

In the foregoing embodiment, the electron injection type multiplication layer **11** in which an ionization rate (α) of electrons is larger than an ionization rate (β) of holes has been described as an example. As in the present modification, even in a configuration including the hole injection type multiplication layer **11**C in which β is larger than α, effects similar to those of the foregoing embodiment can be exhibited.

## Second Embodiment

FIG. **12** is a cross-sectional view illustrating a structure of an optical waveguide type photodetector **2**E according to a second embodiment and illustrates a cross section corresponding to line V-V in FIG. **1**. In place of the multiplication layer **11** and the p-type electric field control layer **12** of the first embodiment, the photodetector **2**E includes the multiplication layer **11**A and the p-type electric field control layer **12**A. The multiplication layer **11**A has the same composition and thickness as the multiplication layer **11** of the first embodiment. The multiplication layer **11**A is provided only between the region D of the n-type semiconductor layer **10** and the optical absorption layer **13** and does not extend to a part between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. The p-type electric field control layer **12**A has the same composition and thickness as the p-type electric field control layer **12** of the first embodiment. The p-type electric field control layer **12**A is provided only between the region D of the n-type semiconductor layer **10** and the optical absorption layer **13** and does not extend to a part between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. The p-type electric field control layer **12**A is a seventh semiconductor layer in the present modification.

The photodetector **2**E further includes a p-type semiconductor layer **83**. The p-type semiconductor layer **83** is a sixth semiconductor layer in the present modification. The p-type semiconductor layer **83** is provided on the region E of the n-type semiconductor layer **10**, and the optical waveguiding core layer **81** is provided on the p-type semiconductor layer **83**. That is, the p-type semiconductor layer **83** is provided between the region E of the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. The optical waveguiding core layer **81**, the cladding layer **82**, and the p-type semiconductor layer **83** constitute an optical waveguide structure **80**B according to the present embodiment.

The optical waveguiding core layer **81** is optically coupled to the optical absorption layer **13**. For example, a butt joint interface between the optical waveguide structure **80**B and the photodiode structure **19** is formed through wet etching. Hence, the butt joint interface is inclined with respect to a direction perpendicular to an upper surface of the n-type semiconductor layer **10** (that is, an interface between the n-type semiconductor layer **10** and the multiplication layer **11**A). In other words, when the interface between the optical waveguide structure **80**B and the pho-

todiode structure **19** is a first interface C**3** and the interface between the region D of the n-type semiconductor layer **10** and the photodiode structure **19** is a second interface C**4**, the angle θ formed by the first interface C**3** and the second interface C**4** is smaller than 90°.

The p-type semiconductor layer **83** has a larger refractive index than the n-type semiconductor layer **10** and is formed of a material which can be subjected to lattice matching with the n-type semiconductor layer **10**. For example, the p-type semiconductor layer **83** is made of InGaAsP. For example, a bandgap wavelength of InGaAsP of the p-type semiconductor layer **83** is equivalent to that of the optical waveguiding core layer **81**. For example, a bandgap wavelength of InGaAsP of the p-type semiconductor layer **83** is 1.05 μm. For example, the p-type semiconductor layer **83** is a low-concentration p-type InGaAsP layer of which the Zn-doping concentration is $3\times10^{16}$ $cm^{-3}$ or lower. An impurity concentration of the p-type semiconductor layer **83** is lower than an impurity concentration of the p-type electric field control layer **12**A. For example, a thickness of the p-type semiconductor layer **83** is within a range of 0.050 μm to 0.200 μm. The p-type semiconductor layer **83** ascends on the end face of the photodiode structure **19** along the first interface C**3**. The p-type semiconductor layer **83** comes into contact with the multiplication layer **11**A, the p-type electric field control layer **12**A, the optical absorption layer **13**, and the p-type semiconductor layer **14** in the first interface C**3**.

The cladding layer **82** has a smaller refractive index than the p-type semiconductor layer **83** and the optical waveguiding core layer **81** and is formed of a material which can be subjected to lattice matching with the optical waveguiding core layer **81**. For example, the cladding layer **82** is made of undoped InP. A part of the n-type semiconductor layer **10**, the p-type semiconductor layer **83**, the optical waveguiding core layer **81**, and the cladding layer **82** constitute a stripe mesa structure extending in the optical waveguiding direction. An optical signal is confined inside the p-type semiconductor layer **83** and the optical waveguiding core layer **81** due to this stripe mesa structure and differences between refractive indices of the n-type semiconductor layer **10** and the cladding layer **82**, and the p-type semiconductor layer **83** and the optical waveguiding core layer **81**, and the optical signal can be propagated to the photodetector portion **6***d*. The side surfaces and the upper surface of this stripe mesa structure are protected by being covered by the insulating films **16** and **17** (refer to FIG. **4**).

Also in the photodetector **2**E of the present embodiment, similar to the first embodiment, the photodiode structure **19** includes the multiplication layer **11**A and the p-type electric field control layer **12**A. Accordingly, the photodiode structure **19** having an avalanche multiplication action can be obtained.

In the photodetector **2**E of the present embodiment, the p-type semiconductor layer **83** having a lower impurity concentration than the p-type electric field control layer **12**A is provided between the n-type semiconductor layer **10** and the optical waveguiding core layer **81**. The p-type semiconductor layer **83** comes into contact with the multiplication layer **11**A and the p-type electric field control layer **12**A in the first interface C**3**. FIG. **13**A is an enlarged view of a part in the vicinity of the end face **11***j* of the multiplication layer **11**A in such a case. A region surrounded by the dotted line in the diagram shows a depleted region. When the p-type semiconductor layer **83** comes into contact with the multiplication layer **11**A and the p-type electric field control layer **12**A, at the time of applying a reverse bias, a part in the vicinity of the end face **11***j* of the multiplication layer **11**A is supplemented with carriers from the p-type semiconductor layer **83**. Therefore, as illustrated in FIG. **13**A, the depletion range Ws of a part in the vicinity of the end face **11***j* of the multiplication layer **11**A expands. That is, according to the photodetector **2**E, the depletion range of the multiplication layer **11**A can be made approximately uniform from a central part to a part in the vicinity of the end face **11***j*.

FIG. **13**B is a view illustrating change in electric field intensity of the multiplication layer **11**A in the thickness direction. According to the present embodiment, the maximum electric field Emax of a part in the vicinity of the end face **11***j* of the multiplication layer **11**A becomes equivalent to the maximum electric fields of other parts in the multiplication layer **11**A. That is, partial increase in maximum electric field Emax in the multiplication layer **11**A can be curbed. Therefore, edge breakdown can be made unlikely to occur, and deterioration in reliability due to concentration of a multiplication current can be avoided.

Hereinabove, the present disclosure has been described specifically on the basis of examples, but the present disclosure is not limited to the foregoing examples and can be changed within a range not departing from the gist thereof. For example, each of the embodiments and each of the modifications described above may be combined together as necessary in accordance with the purpose and the effect. A specific composition of each of the semiconductor layers is not limited to the foregoing examples. In the foregoing embodiment, a configuration in which the optical waveguide portions **8***a*, **8***b*, **8***c*, **8***d*, **8***e*, and **8***f* and the light receiving element portions **6***a*, **6***b*, **6***c*, and **6***d* are integrated on the common substrate **9** has been described as an example. A photoelectric conversion circuit including other InP-based electronic devices (for example, hetero junction bipolar transistors), capacitors, and resistors may be further integrated on the substrate **9**. In the foregoing embodiment, the n-type semiconductor layer **10** is provided on the substrate **9**. When a substrate is an n-type semiconductor substrate, the n-type semiconductor layer **10** may be omitted. In such a case, the n-type semiconductor substrate becomes the first semiconductor layer, and all the relationships between the n-type semiconductor layer **10** and other semiconductor layers in the foregoing description can be read as relationships between the n-type semiconductor substrate and other semiconductor layers.

In each of the embodiments and each of the modifications described above, a case in which the present disclosure is applied to an integrated photodetector used by a coherent wave detection method using quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM) has been described. The present disclosure may be applied to an optical waveguide type photodetector of a method of directly detecting an intensity modulation signal such as Non-return to Zero (NRZ) or 4-level pulse amplitude modulation (PAM4).

FIG. **14** is a plan view illustrating an example of such an optical waveguide type photodetector. An optical waveguide type photodetector **2**F illustrated in FIG. **14** includes the semi-insulating substrate **9** (not illustrated in FIG. **14**), the n-type semiconductor layer **10**, the optical waveguide portion **8**, and the photodetector portion **6**. The n-type semiconductor layer **10** is provided on the substrate **9**. The optical waveguide portion **8** and the photodetector portion **6** are provided on the n-type semiconductor layer **10**. The optical waveguide portion **8** has any of the optical waveguide structures **80** and **80**B of each of the embodiments and each of the modifications described above. The photodetector portion **6** has any photodiode structure **19** of each of the

embodiments and each of the modifications described above. Moreover, this photodetector **2**F includes the multiplication layer **11** or **11**A described above and the p-type electric field control layer **12** or **12**A.

In this example, the electrode pad **23** and a wiring on the p-type ohmic electrode are electrically connected to each other via a wire **71**. The bias wiring provided on the n-type ohmic electrode is electrically connected to a pair of electrode pads **22***e* and **22***f* provided on both sides of the photodetector portion **6**. The configurations of this modification can also exhibit effects similar to those of the foregoing embodiment. In this example, the multiplication layer **11**C of FIG. **11** may be provided in place of the multiplication layer **11** or **11**A, and the p-type electric field control layer **12**C of FIG. **11** may be provided in place of the p-type electric field control layer **12** or **12**A. The p-type semiconductor layer **101** of FIG. **11** may be provided in place of the n-type semiconductor layer **10**, and the light receiving element portion **6** may have the photodiode structure **117** of FIG. **11** in place of the photodiode structure **19**.

What is claimed is:

**1**. An optical waveguide type photodetector comprising:

a first semiconductor layer of a first conductive type;

a multiplication layer being of a first conductive type and provided on the first semiconductor layer;

an optical waveguide structure having an end face and provided on a first region of the first semiconductor layer and including an optical waveguiding core layer and a cladding layer; and

a waveguide type photodiode structure having an end face and provided on a second region of the first semiconductor layer and having a third semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or of a second conductive type, and a second semiconductor layer being of a second conductive type which are arranged in this order,

wherein the end face of the waveguide type photodiode structure and the end face of the optical waveguide structure are in contact.

**2**. The optical waveguide type photodetector according to claim **1**, wherein

the multiplication layer is between the first semiconductor layer and the optical waveguiding core layer and,

the optical waveguiding core layer is provided throughout an entire area of the optical waveguide structure.

**3**. The optical waveguide type photodetector according to claim **1**, further comprising:

a buffer layer provided between the first semiconductor layer and the multiplication layer, the buffer layer being of a first conductive type having a lower impurity concentration than the first semiconductor layer or being an undoped layer, and

a fourth semiconductor layer provided between the buffer layer and the multiplication layer, the fourth semiconductor layer being of a first conductive type having a higher impurity concentration than the multiplication layer.

**4**. The optical waveguide type photodetector according to claim **1**,

wherein the waveguide type photodiode structure further includes another semiconductor layer provided between the third semiconductor layer and the optical absorption layer.

**5**. The optical waveguide type photodetector according to claim **4**,

wherein the another semiconductor layer does not extend to a part of the first region of the first semiconductor layer.

**6**. The optical waveguide type photodetector according to claim **1**,

wherein an angle between the end face of the waveguide type photodiode structure and a plane of the third semiconductor layer is smaller than 90°.

**7**. The optical waveguide type photodetector according to claim **1**, further comprising:

a first ohmic electrode provided on the first semiconductor layer located outside the waveguide type photodiode structure;

a contact layer of a second conductive type provided on the second semiconductor layer; and

a second ohmic electrode provided on the contact layer.

**8**. The optical waveguide type photodetector according to claim **1**, further comprising:

a semi-insulating substrate,

wherein the first semiconductor layer is provided on the semi-insulating substrate.

**9**. The optical waveguide type photodetector according to claim **1**,

wherein the first semiconductor layer and the second semiconductor layer are InP layers,

wherein the optical absorption layer is an InGaAs layer,

wherein the multiplication layer is an InAlAs layer, and

wherein the third semiconductor layer is an InP layer or an InAlGaAs layer.

**10**. The optical waveguide type photodetector according to claim **1**,

wherein the third semiconductor layer is formed in both the first region and the second region of the first semiconductor layer.

**11**. An optical waveguide type photodetector comprising:

a first semiconductor layer of a first conductive type;

an optical waveguide structure having an end face and provided on a first region of the first semiconductor layer and including an optical waveguiding core layer and a cladding layer;

a waveguide type photodiode structure having an end face and provided on a second region of the first semiconductor layer and having a multiplication layer being of a first conductive type, another semiconductor layer being of a second conductive type, an optical absorption layer being of an intrinsic conductive type or a second conductive type, and a second semiconductor layer being of a second conductive type which are arranged in this order, the end face of the waveguide type photodiode structure facing the end face of the optical waveguide structure; and

still another semiconductor layer of a second conductive type located between the end face of the optical waveguide structure and the end face of the waveguide type photodiode structure and in contact with the multiplication layer at the end face of the waveguide type photodiode structure.

**12**. The optical waveguide type photodetector according to claim **11**,

wherein the multiplication layer and the another semiconductor layer do not extend to between the first region of the first semiconductor layer and the optical waveguiding core layer.

**13**. The optical waveguide type photodetector according to claim **11**,

wherein a bandgap of the still another semiconductor layer is equivalent to a bandgap of the optical waveguiding core layer.

**14**. The optical waveguide type photodetector according to claim **11**,

wherein a thickness of the still another semiconductor layer is within a range of 0.050 μm to 0.200 μm.

**15**. The optical waveguide type photodetector according to claim **11**,

wherein an impurity concentration of the still another semiconductor layer is lower than an impurity concentration of the another semiconductor layer.

**16**. The optical waveguide type photodetector according to claim **11**,

wherein the first semiconductor layer and the second semiconductor layer are InP layers,

wherein the optical absorption layer is an InGaAs layer,

wherein the multiplication layer is an InAlAs layer,

wherein the sixth semiconductor layer is an InGaAsP a layer, and

wherein the seventh semiconductor layer is an InP layer or an InAlGaAs layer.

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